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MEASUREMENT OF SPACE CHARGE IN THE LOWER ATMOSPHERE

FINAL REPORT. CONTRACT No. AF 61(514)-891

By J. Alan Chalmers, M.A., Ph.D., F.Inst.P.
and W. Smiddy, Ph.D.

Physics Department, Durham Colleges in the University of Durham.

FC

The research reported in this document has been sponsored by the Geophysics Research Directorate of the Air Force Cambridge Research Center, AIR RESEARCH AND DEVELOPMENT COMMAND, UNITED STATES AIR FORCE under Contract No. AF 61(514)-891, through the European Office, ARDC.

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SUMMARY

A double field mill is described which, when placed at a point above the earth's surface, is automatically brought to the potential of that point and registers the potential and the potential gradient. Two such instruments are employed to study space charge values in the first five metres of the atmosphere.

Greek MJ

Results in fine weather indicate values of the order of $-50\ \mu\mu c/m^3$ close to the ground and values around zero for 1-3 metres; the height to which the negative charge extends depends upon the potential gradient and this agrees with the view that it is caused by ionization from radio-active substances in the surface layers of the earth.

Comparison with results for space charge using an Obolensky-type filter show good agreement, except when small ions are present in large numbers.

Results in light or moderate rain show that little, if any, space charge is produced. In heavy rain, there appears to be formed a space charge of around $-1000\ \mu\mu c/m^3$. In snowfall, space charges of both signs are found of about $\pm 500\ \mu\mu c/m^3$.

Greek MJ

FOREWORD

In this work, the rationalized MKS system of units is used throughout. The figures used were originally prepared and numbered for another purpose, and some of those figures were not required here. To avoid re-numbering and re-drawing, there will be found some gaps in the numbering.

The symbols v., a., c. and Ω are used for volts, amperes, coulombs and ohms, while k, M. denote 10^3 Ω and 10^6 Ω. The symbol μ refers to 10^{-6} and μμ to 10^{-12}.

ACKNOWLEDGEMENTS

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CONTENTS

CHAPTER I. INTRODUCTION

1·1. Problems Involving Space Charge.

By the term "space charge" is meant the excess of charge of one sign in a volume of the atmosphere. There are two problems in atmospheric electricity in which some progress can be made by investigation of the space charge present in the lowest levels of the atmosphere.

If the lower atmosphere behaves as a medium which is uniformly ionized, then there should be evident an "electrode effect" [see para. 2·3] and this gives rise to a space charge in the lowest levels of the atmosphere. However, this is normally not found and it seems that measurement of the space charges present may help to solve the problem.

In continuous rain, the potential gradient is usually found to be negative and it has been suggested that this arises from negative charge produced by the splashing of the rain at the earth's surface. Investigation of the space charge near the ground during rain can assist in assessing the merits of this theory.

CHAPTER II. SPACE CHARGE

2·1. Classification of Space Charge.

Charged bodies in the atmosphere may consist of small ions, large ions, smoke or dust particles, mist or fog droplets or precipitation particles. A space charge exists when there is an excess of positive charges on these bodies over negative charges or vice versa; although it may happen that some of the bodies enumerated above may be absent, it is often not possible to ascertain that the space charge is concerned only with one class.

It is possible to divide space charges into two general classes; the first, which we shall term primary space charge, concerns space charges which are produced by some natural or artificial process at some distance from the place of observation and which are then transported to this place; a simple example is the charge on precipitation particles, while another is seen in charge clouds produced by industrial processes. On the other hand, what we can term secondary space charge consists of large and small ions, for which an excess of one sign arises from the processes of conduction in the air; an example is seen in the electrode effect. To a certain extent, the secondary space charges reside on ions and the primary space charges on larger particles but this is by no means invariably true.

2·2. Relation between Space Charge, Potential Gradient and Conductivity.

We can define a "quasi-static" state in the atmosphere, such that an instantaneous picture of the electric charges in the atmosphere would always be the same, although the actual charges may be moving. If we consider the atmosphere to be, electrically, horizontally stratified, then the conduction current must be vertical and in a quasi-static state the current density must be the same at all levels.

If i is the current density, F the potential gradient and λ the conductivity, then :

$$i = \lambda F$$

Thus, if λ alters with the level, it follows that F must also alter.

Now, Poisson's law gives :

$$\rho = -\epsilon_0 \, dF/dx$$

where ρ is the space charge density.

Therefore a difference of conductivity at different levels gives rise to a space charge, which is what we have defined as a secondary space charge.

Considering the resistivity $r = 1/\lambda$, then

$$F = i\,r$$

$$dF/dx = i\,dr/dx$$

$$\rho = -\frac{i}{\epsilon_0}\frac{dr}{dx}.$$

Integrating, there is a charge q per unit cross-sectional area between two levels where the resistivities are r_1 and r_2 such that :

$$q = -\frac{i}{\epsilon_0}\,[r_1 - r_2]$$

$$\text{or}\quad q = -\frac{i}{\epsilon_0}\,[1/\lambda_1 - 1/\lambda_2]$$

2·3. The Electrode Effect.

If a volume of air is ionized uniformly and then subjected to an electric field between two electrodes, it would, at first sight, be expected that the potential gradient between the electrodes would be and remain uniform. However, this is not so, and in fact the potential gradient becomes non-uniform with, in correspondence, a space charge.

If we consider a region close to one electrode, say the negative electrode, then in conditions of uniform ionization and uniform potential gradient, there will be a current of positive ions into the region from the direction of the positive electrode and an equal current of positive ions out of this region into the negative electrode; at the same time, there will be a current of negative ions from the region towards the positive electrode, but there can be no corresponding current of negative ions into the region unless there is a source of negative ions at the negative electrode. In the absence of such a source, there must be more negative ions leaving the region than entering it, thus giving the region a positive space charge and rendering the potential gradient non-uniform. The positive space charge builds up until the non-uniformity of the potential gradient becomes such that the difference of the positive ion currents from and to the region becomes equal to the negative ion current from the region, after which the space charge in the region, and the values of the potential gradients at different places remain constant.

This space charge and non-uniform potential gradient is termed the "electrode effect" and has been identified in laboratory measurements. The exact amount of space charge and the change in potential gradient from the electrode to a point well away can be calculated if suitable assumptions are made in regard to the rate of production of ions and the interactions of small ions, large ions and uncharged nuclei.

If the idea of the electrode effect is applied to conditions in the atmosphere, with the earth as the negative electrode, calculations made with somewhat different assumptions by Schweidler (1908), Behacker (1910), Swann (1913) and Scholtz (1931) all show that the potential gradient at 1 m should be about 30 per cent less than at ground level, with a corresponding positive space charge in the lowest metre of the air.

All measurements under normal conditions have shown that there is certainly not this difference of potential gradient nor the space charge predicted. Therefore the electrode effect in its simple form is not manifested in the lowest levels of the atmosphere. However, it is necessary to point out that one would expect the electrode effect to appear, as calculated, only if the conditions are completely undisturbed, and there may be some doubt whether previous measurements do satisfy this condition as closely as might be desired. Hitherto, it has not been possible to measure, directly, the potential gradient above the earth's surface, and measurements of the potential by radioactive collectors introduce extra ionization. Further, any apparatus for direct measurement of space charge must also disturb the natural conditions.

We can consider the electrode effect in terms of the considerations of para. 2.2. If no ions can reach the lowest regions of the atmosphere from the ground, the conductivity there must be less than higher up and so there must be a space charge which is positive.

2.4. Convection Currents.

The electrode effect, as calculated, involves the assumption that the air is at rest; it has therefore been suggested that the reason that the electrode effect is not observed is that it is obscured by motion of the air. If there is a space charge and motion of the air transports this upwards, then the convection current arising in this way must be taken into account in discussing the quasi-static state. Whipple (1932) made calculations on this basis, but the space charge and change of potential gradient required appear to be greater than has been found by observations. The idea of a space charge arising from the electrode effect and transported by convection has been revived by Kasemir (1956) in an attempt to account for the "sunrise-effect", and this makes it even more desirable to investigate the space charge in the undisturbed lowest regions of the atmosphere.

2.5. Effect of Radioactivity.

Since the electrode effect corresponds to a decrease in conductivity on approaching the earth's surface, this could be counteracted by some other process giving an increase of conductivity near the surface. Hogg (1939) made the suggestion that α- and β- radiation from radioactive substances in the earth's surface would provide just such an increase in conductivity and Chalmers (1946) made some calculations which showed how the absence of the electrode effect could be explained on reasonable values of the rate of ionization. Since the balancing of the electrode effect and the radioactive effect cannot be exact at all levels, measurements of space charge can be of assistance in discovering how far this explanation is tenable.

It should be emphasised that considerations of the electrode effect are based on quasi-static conditions and so can be applied to long-term averages and not to short-term fluctuations of potential gradient and space charge.

CHAPTER III. SPACE CHARGE DETERMINATION

3·1. Methods of Measurement of Space Charge.

Various methods have been used to measure space charge in the atmosphere near the ground; a critical summary has recently been given by Vonnegut and Moore (1958). The methods can be conveniently divided into 3 main classes.

In the first type of method, the air to be investigated blows into an earthed cage and the potential at a point inside the cage is measured. Care must be taken that the cage shall not carry an induced charge which would attract ions of one sign and repel those of opposite sign. This method was first suggested by Kelvin (1862) and was used by Chauveau (1902) and, more accurately, by Kähler (1927); Kähler used a water dropper to measure the potential at a point inside the cage, while Vonnegut and Moore (1958) used various methods, finally preferring a Polonium collector; Mühleisen and Holl (1952), instead of finding the potential acquired by an insulated dropper, measured the charges on drops falling from an earthed dropper.

In the second type of method, the air is drawn through a filter and the charge trapped by the filter is measured. Again, care must be taken in regard to induced charges. This method was used by Obolensky (1925) and Brown (1930); Kinman (1954) made careful comparisons between apparatus of this type and that of the cage type and found good agreement. Vonnegut and Moore (1958) thought that some space charge, residing on large ions, might not be trapped. Of rather similar type to this method is a method of counting ions of both signs and finding the difference; a difficulty arises here in regard to space charges on particles of low mobility.

The third type of method involves the use of Poisson's law by measuring the vertical potential gradient at different levels. Daunderer (1907, 1909) used lamps as potential equalizers and placed them at heights of 0, 1 and 2 m, measuring the potential difference between them; Norinder (1921) and Scrase (1935) used stretched wires with radioactive collectors at their mid-points; Norinder measured simultaneously the potentials acquired by wires at different levels, whereas Scrase measured the potential differences between 2 wires 1 m apart at different mean heights.

Some results are given in Table I.

Most workers have given their results in E.S.U/cc. or E.S.U/m^3. To convert to M.K.S. units, 1 E.S.U = $3{\cdot}33 \times 10^{-10}$ coulombs. The results will here be given in $\mu\mu c/m^3 = 10^{-12}\ c/m^3$.

TABLE I

METHOD	OBSERVER	HEIGHT RANGE	LOCATION	TIME	VALUE ESU/m^3	MEAN ANNUAL	YEAR
Water dropper in Faraday Cage	Kähler		Potsdam	Nov. Jan. Feb. June, July Aug.	+0.67 +0.36	+0.58	1922 1 yr.
Flame collector	Daunderer	0-3m.	Bad Aibling	March-June Jan.-March July-Nov.	+0.616 -0.577 +0.630	+0.115	1906 1 yr.
Water dropper and Radioactive Collector	Norinder	0-3m. Fixed system	Upsala	Summer Winter Spring-Autumn	-0.07 -0.20 -0.11	-0.12	1918 and 1919 2 yr.
Radioactive collector	Scrase	1-10m.	Kew	Turbulent Air Still Air	+0.02 +0.04	+0.03	1924 1 yr.
Filtration Method	Obolensky	1m.	Pavlosk	Dec.-Feb July-Sept.	+0.051 -0.095	0.003	1924 1 yr.
Filtration Method	Brown	7.5m.	San-Francisco	Sept.-Feb. March-Aug.	+0.098 +0.072	+0.083	1929 1 yr.
Ion Counter	Ebert	-	-	-	-	+0.09	
Ion Counter	Gockel	-	-	-	E^+=0.32 E^-=0.33	-0.01	19?7 1 yr.

3·2. Choice of Method.

In order to be able to use a method of space charge measurement for the purpose of investigating secondary space charge, as defined above (para. 2·1), it is necessary to avoid, as far as possible, any disturbance of the natural electric state in the atmosphere. Apparatus of the cage or filtration type is bound to cause some disturbance of the electrical conditions, particularly if precautions are taken to avoid effects of induced charges, either by extra shielding or by increasing the rate of air flow. Therefore it seemed better to use the method involving Poisson's law; this has the added advantage that it is simpler than for the other methods to make measurements at different heights.

For measurements where it is essential not to disturb natural conditions, there are grave disadvantages in using radioactive collectors, as they produce extra, unwanted, ionization in the region investigated. For this reason, it seemed to be better to use the "field machine" type of method of measuring potential gradients. As normal field machines operate to measure the potential gradient at ground level, it was necessary to adapt the method to the measurement of potential gradient at points above ground level without disturbance of the electrical conditions. There is a further advantage of the field machine method, namely that it measures directly the potential gradient whereas radioactive collectors measure only potentials.

3·3. Numerical Values.

The numerical values obtained for the space charge in the lower atmosphere have mostly been less than 0·1 ESU/m^3 = [illegible]·3 $\mu\mu$ c/m^3.
For this value,

$$\frac{dF}{dx} = \frac{\rho}{\epsilon_0} = -3{\cdot}76 \text{ v/m./m.}$$

Since the normal value of the potential gradient is of the order of 100 v./m., it will be necessary to measure alterations of this, over 1 m of height, of a few per cent.

3·4. Principle of the Double Field Machine.

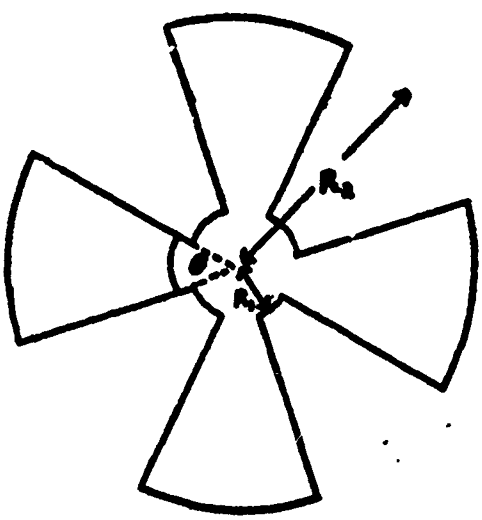
Consider a thin conducting disk of area A placed with its surfaces horizontal. If the disk carries no resultant charge and is placed where there is a vertical potential gradient, F, the upper surface of the disk will carry a charge $-Q = -\epsilon_0 FA$ and the lower surface a charge $+Q$.

If, on the other hand, the disk is situated in a region with no external field and carries a total charge of + 2q, then each surface carries a charge of + q.

Electrostatic theory shows that, if the disk is situated in a field and carries a resultant charge, then it is possible to add the two results above. Thus the upper surface carries a charge $X = -Q + q$, and the lower surface a charge $Y = +Q + q$. The measurement of $Y - X$ thus gives 2Q, irrespective of the value of q. This is the principle of the method used by Gunn (1948), Gish and Wait (1950) and others to obtain the potential gradient by measurements with two field mills, symmetrically placed on an aircraft, to obtain the potential gradient in the air.

Although the measurement of $Y - X$ gives the value of 2Q and hence of F, whatever is the value of q, there is bound to be distortion of the field unless q is zero, and this is bound to affect space charges. In order to avoid distortion, $X + Y = 2q$ must be made zero; if $X + Y$ is positive, there must be a reduction of q, i.e. a reduction of the potential of the disk, relative to earth, and correspondingly an increase if $X + Y$ is negative.

Provided the sign of F is known, it is not necessary to know the signs of X and Y. If F, and so Q, is positive, then, when q is positive, whether greater or less than Q, both terms in Y are positive, while only one in X is, so that $Y > X$ and, even if X is negative, $|Y| > |X|$; similarly when q is negative, $|X| > |Y|$. so that the potential of the disk, and thus q, can be regulated by the relative values of $|X|$ and $|Y|$. On the other hand, when F, and so Q, is negative, then with q positive, $|X| > |Y|$ and with q negative, $|X| < |Y|$; thus when F changes sign, the direction of the change of regulating potential must also change.



$\theta = \frac{\pi}{N}$

Fig 2a

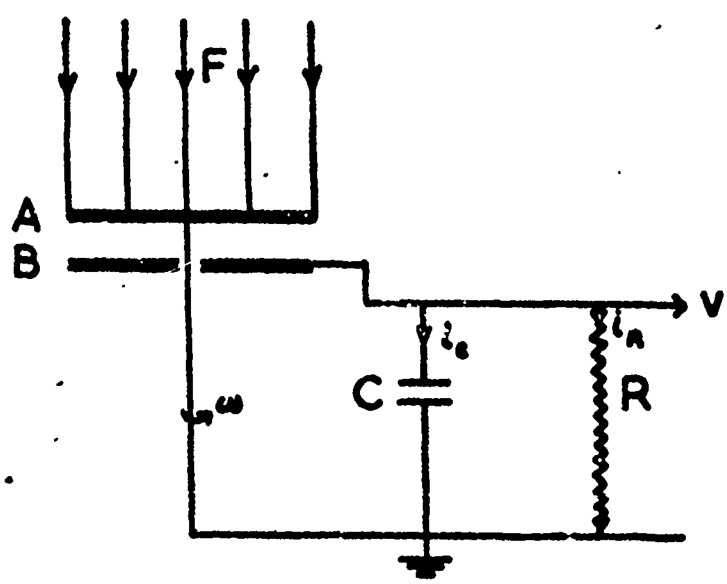


Fig 2b

CHAPTER IV. THE DOUBLE FIELD MILL

4·1. Design Considerations.

It was decided to construct a sector-type field mill, the theory of which has been worked out by Mapleson and Whitlock (1955). Their mill had an accuracy of measurement of potential gradient to ± 1 v/m over a range -75 to + 75 v/m with a background noise equivalent to ½ v/m within a frequency range 0·1 to 10 c/s, so that this seems to be very suitable for the present purpose.

Fig. 2a shows the shape of the rotating and fixed vanes, shown at A and B in Fig. 2b, giving the fundamental output circuit of the mill.

Whitlock (1955) has shown that, on applying a potential gradient F at time t = 0, the output after an infinite time is:

$$V = \frac{\epsilon_o F N w R}{2} (r_2^2 - r_1^2) \quad \frac{1 - \exp(-\pi/NwRc)}{1 + \exp(-\pi/NwRc)}$$

where w is the rate of revolution in radians/sec and the other quantities are seen in Fig. 2.

If $\pi/NwRc \ll 1$, and expanding the exponential terms,

$$V \sim \frac{\epsilon_o F \pi (r_2^2 - r_1^2)}{4C}$$

which is independent of small changes in w.

If the smallest potential gradient to be measured is 1V/m, and if 0·1 mV can be measured, then C must be less than 360 μμf.

The output from the mill has high impedance and this has to be matched to the low impedance of the cable to the amplifier through a cathode follower. If the grid current of the cathode follower valve is Ig, the D.C. voltage across the input resistor is RIg. The valve used was a Mullard EF37a run at reduced heater and anode potentials; the grid current was measured to be 10^{-10}a.

The capacitance of the stator-rotor assembly and connecting cables, C, was measured to be 60 μμf and the variation, ΔC, in this from exposed to screened position was 4 μμf. The variation in vane capacitance gives an A.C. component of the same frequency as the signal, of magnitude

$$Vc = \frac{\Delta C}{C} RIg$$

This can be reduced by increasing C to 260 μμf, still below the value given above as the maximum.

If Vc is now to be 10% of V for 1 v/m, it turns out that R < $0{\cdot}9 \times 10^7$ ohms.

To keep Nw > π/RC, we must now make w > 2900 r.p.m.

Using a motor speed of 1,425 r.p.m., with pulleys of radii 7·2" and 3·42", the mill speed is 3000 r.p.m.

Inserting the final values,

$$V = 1{\cdot}4 \times 10^{-4} F[1 - 7{\cdot}7 \times 10^{-2}]$$

where the second term in the brackets is proportional to w^2; a 1% change in w gives only 0·17% change in V.

4·2. Mounting and Driving of the Mills.

Because the double field mill will be considerably heavier and more bulky than the water droppers or radioactive collectors used by Norinder and Scrase, it will require a more rigid supporting structure. In deciding what form the supports must take, it must be borne in mind that a too massive structure will probably distort the earth's field unduly and so destroy the whole purpose of constructing the mills, namely, to measure values of potential gradient without introducing distortion.

Two effects are likely to arise from the supports:

(1) Any conducting parts which are not at the potential of their surroundings will distort the field.

(2) Any insulating parts are likely to acquire charge and must therefore be placed at such a distance from the mill as not to influence the field there.

The effect of any object, natural or artificial, near a potential-measuring device can be expressed as a "Reduction Factor" for that particular location and is given by:

$$RF = \frac{\text{Measured value of the potential gradient}}{\text{Value over centre of large conducting plane at same site}}$$

Benndorf (1906) considered reduction factors of various objects and found that a vertical conducting post, one metre in height, has less than 1% influence on the potential gradient, one metre above ground, at a distance of 3 metres.

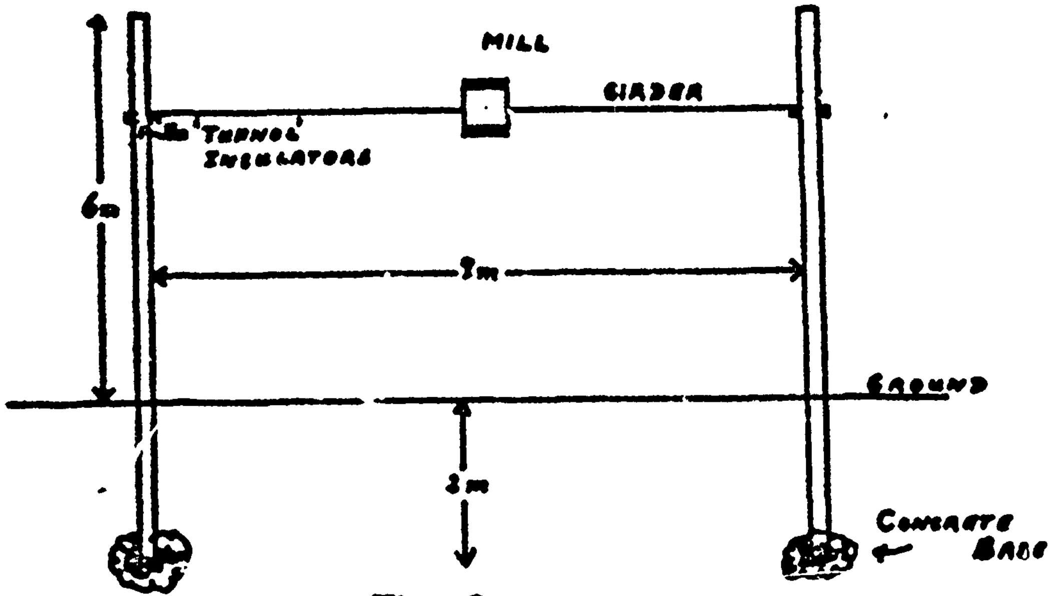

MILL
GIRDER
'THERMOL' INSULATORS
6m
9m
GROUND
3m
CONCRETE BASE

Fig 3a

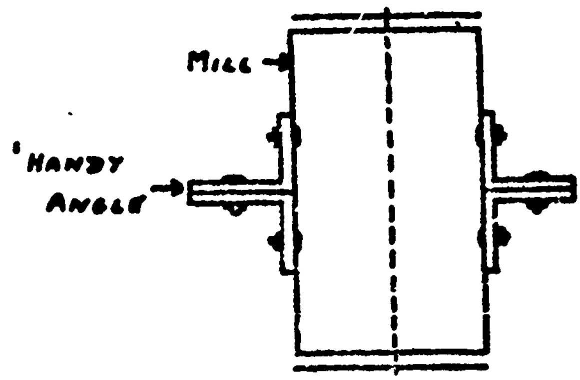
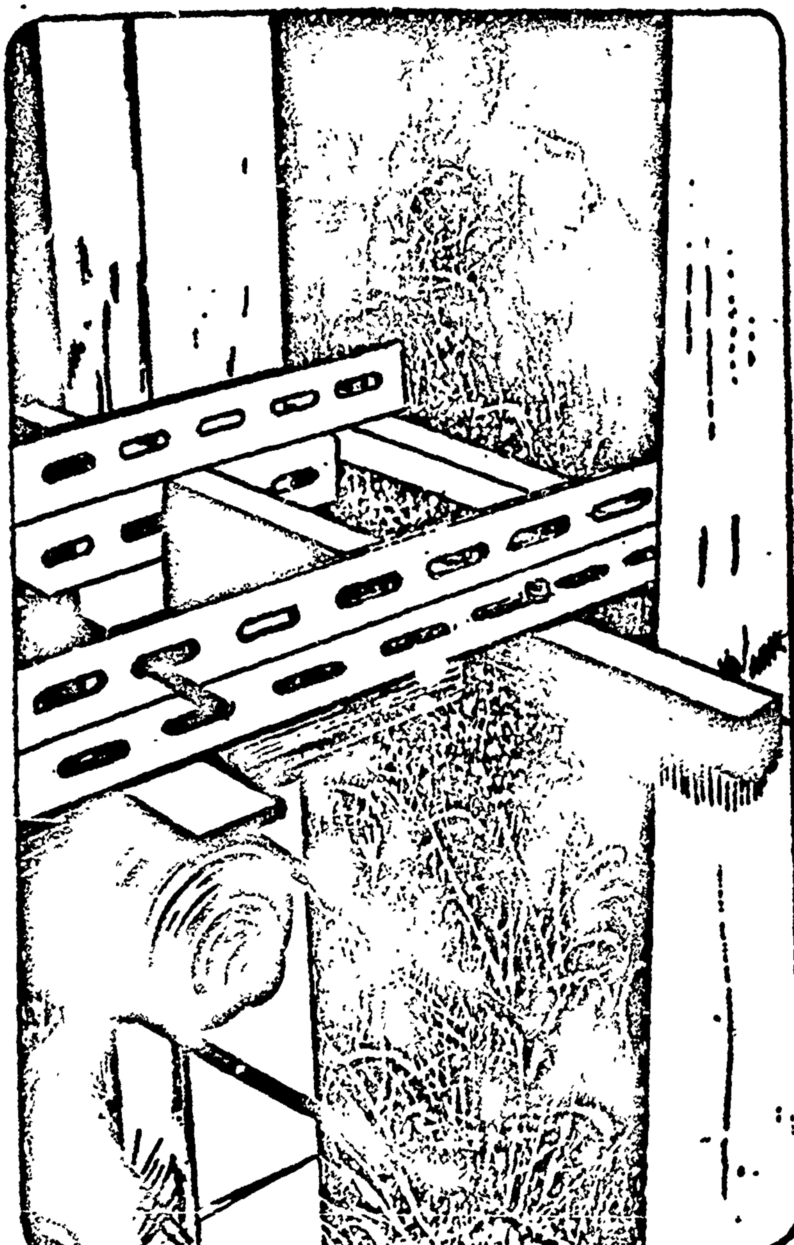

MILL
'HANDY ANGLE'

Fig 3b



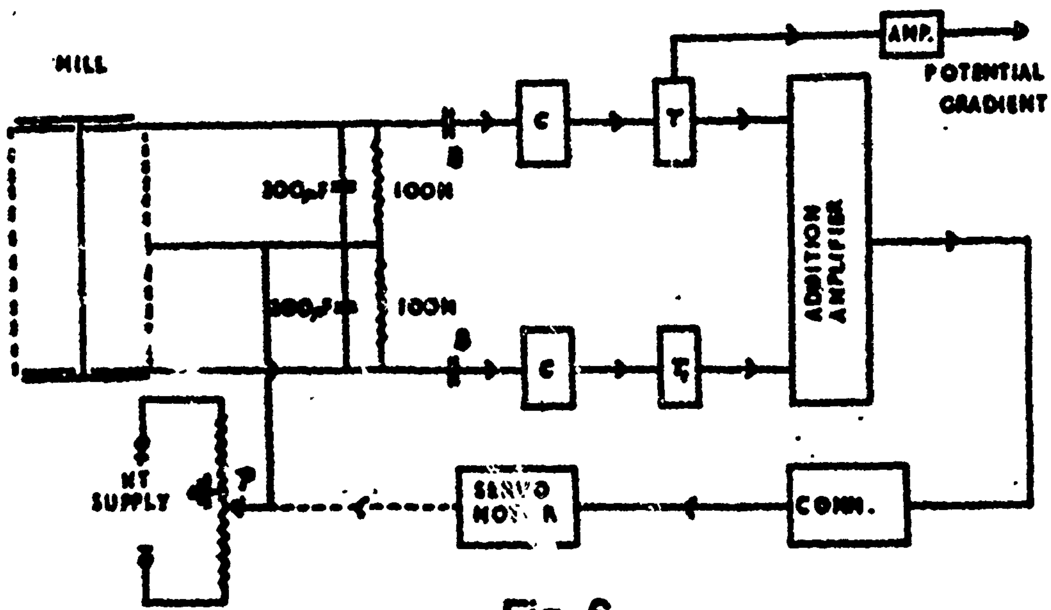

MILL
AMP.
POTENTIAL GRADIENT
C
T
300μF
100M
B
ADDITION AMPLIFIER
HT SUPPLY
P
SERVO MOTOR
COMM.

Fig 6

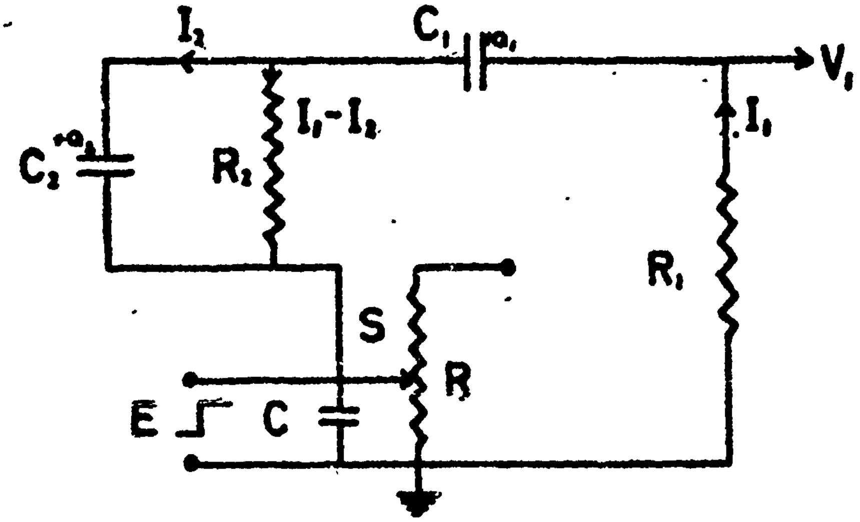

I_2
C_1
V_1
C_2
R_2
$I_1 - I_2$
I_1
R_1
S
R
E
C

Fig 7

of para. 3·4, this can be used to regulate q and hence the mill potential, provided that the direction of motor drive is reversed when F changes sign; or the polarity of the slide potential can be reversed.

The outputs from the upper and lower plates are fed through blocking condensers B to cathode followers C, the condensers isolating "mill earth" from true earth. The cathode follower outputs are fed from the outdoor apparatus through coaxial cable to two matched amplifiers with incorpora rectifiers so as to give a positive polarity to both outputs with respect to earth. These are fed to the two sides of the servo system.

The theory of para. 3·4 shows that, when $|Q| > |q|$ the resultant output is proportional to q and the operation as a collector is satisfactory. But if $|Q| < |q|$, the resultant output is proportional to Q and, if this is small, there may not be enough power to move the slide wire and a balance is not obtained. These peculiar circumstances can be avoided if it is arranged that the mill potential always starts at zero, so that $Y = 0$, $q = -Q$, and henceforth $|Q| > |q|$.

4·4. Time Constant of the Collector System.

It is important to find the response time of the servo-motor to a sudden potential-gradient change, because the value of this compared with the response time of the mill and amplifier circuit is the criterion as to whether the servo-motor will follow changes in potential gradient or will "hunt" and become unstable.

Let τ_1, τ_2 be the time constants of the balancing motor system and of the mill output circuit; then $\tau_1 > \tau_2$ is the condition for stable response. The relevant components of the mill output circuit are shown in Fig. 7; C_2, R_2 are the mill output capacitor and resistor respectively; C_1 is the blocking capacitor B (Fig. 6); R_1 is the input resistor of the cathode follower C (Fg. 6); S is the potentiometer slide of resistance R ohms.

The case to be considered is the behaviour of the circuit when subject to a sudden change in potential gradient, but this may equally well be taken as the case when a step-voltage is applied to the mill; in fact, see para. 5·3, this is more closely the actual case.

Assuming zero initial conditions and solving the problem of the circuit by use of Laplace transformations, it is found that

$$\tau_2 = \frac{2R_1C_1R_2C_2}{R_1C_1 + R_2C_1 + R_2C_2}$$

The capacitance of the mill-girder system to earth is small, so, in order to increase this, and so to make τ_1 large, a 20 μf capacitor is placed between the slide and earth [C in Fig. 7].

The whole slide wire has a resistance of 1 M, divided into 100 parts; if only 1 section, of resistance $10^4\Omega$ is used, $\tau_1 = 1/5$ sec.

$$\text{Thus, for stability,}\quad \frac{2R_1R_2C_1C_2}{R_1C_1 + R_1C_2 + R_2C_2} < \frac{1}{5}$$

$$\text{or}\quad \frac{1}{R_2C_2} + \frac{1}{R_1C_2} + \frac{1}{R_1C_1} > 10$$

If $C_2 = 260\ \mu\mu f$ and $R_2 = 10^8$ ohms, $\frac{1}{R_2C_2} = 38\cdot5$, so that the condition holds whatever the values of R_1 and C_1. Actual values chosen were $R_1 = 1M$ and $C_1 = 10^{-3}\mu f$; this last value gives C_1 a small impedance at the mill frequency, compared with R_2.

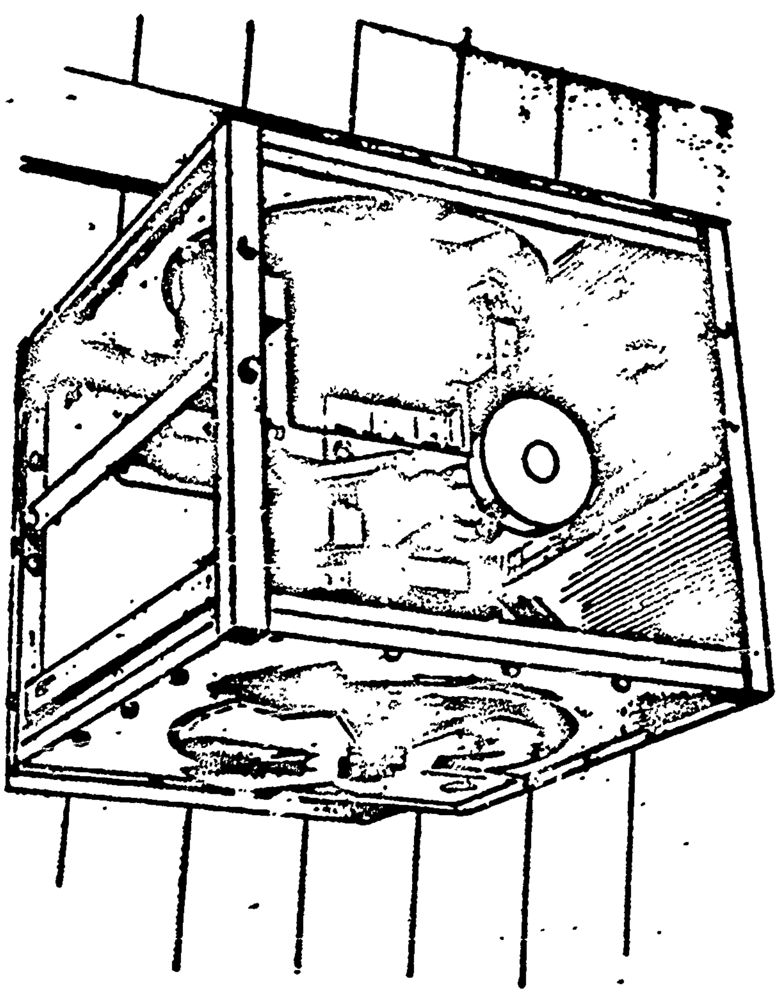


FIG. 8

CHAPTER V. APPARATUS AND EXPERIMENTAL PERFORMANCE

5·1. Field Mill.

The constructional details of the double field mill can be seen clearly from Fig. 8. The drive is transmitted from the horizontal $\frac{1}{4}$" silver steel shaft to the similar vertical vane shaft by means of a 1:1 ratio bevel gear. This gear is situated inside an old electric motor casing which also serves to house the vane shaft. Mounted on top of this casing is a commutator system, by means of which it was hoped to provide a method of sign discrimination of potential gradient; if the amplified mill output is fed back to this system, it will give a rectified output of polarity dependent on the sign of potential gradient; however this system was finally not employed because of unavoidable brush jumping at the high rate of revolution used.

The rotary vanes, identical with the fixed collecting plates, are constructed from $\frac{1}{16}$" stainless steel sheet and mounted at either end of the vane shaft. The collecting plates lie flush with the case of the mill to avoid field distortion and are mounted 6 mm. below the rotating vanes on four highly polished polystyrene insulators.

The whole structure is bolted rigidly to a brass frame, covered with sheet aluminium, into which are fixed two coaxial "Pye" sockets connected to the upper and lower collecting plates. When assembled, the mill has horizontal dimensions of 22 x 22 cm, with 20 cm between the rotating vanes.

Connection is made between the mill and "junction box", situated at the end of the mill-supporting girder, using Uniradio "Telcon" low capacitance PVC insulated coaxial cable. The sheath of this cable is "earthed" to the mill and girder assembly, at the potential of the mill. The "junction box" is the terminating point of the mill potential and contains the mill condenser C_2 and resistor R_2 [see Fig. 7]; the cable capacitance is in parallel with C_2 and so must be kept as low as possible; this value is included in the 60 μμf quoted in para. 4·1.

The mill outputs are then taken through the blocking condensers C_1, which are TCC "Cathodray" "Visconol" condensers having a DC working voltage of 6 kV and a capacitance of 0·001 μf; from the "earthy" side of the junction box, the mill outputs are fed to the cathode followers through Radiospares "Hygrade" coaxial cable, with earthed sheath; similar cable is also [illegible]ed to convey the mill-balancing potential to the mill gi[illegible]r.

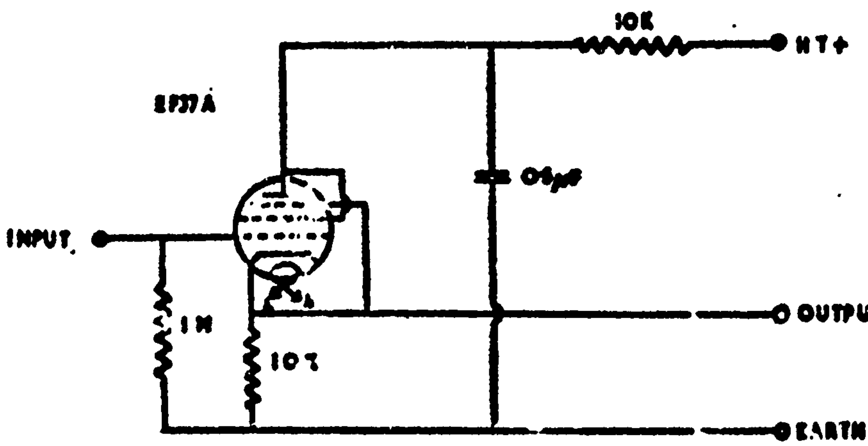

10K
HT+
0·1μF
INPUT
1M
OUTPUT
EARTH

Fig 9

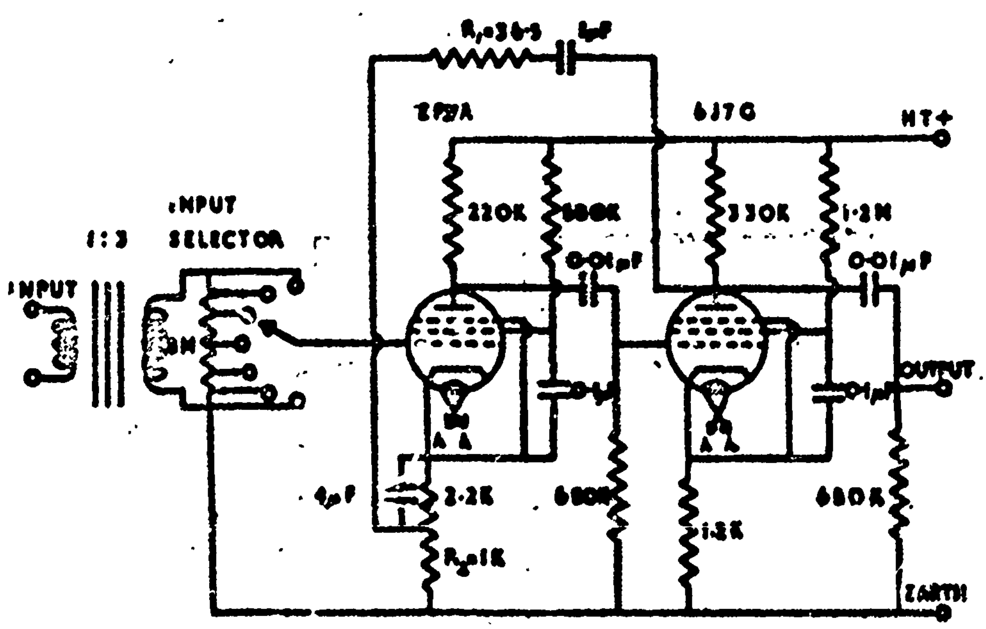

HT+
6J7G
INPUT
SELECTOR
1:3
INPUT
220K
330K
1·2M
0·01μF
OUTPUT
4μF
2·2K
680K
EARTH

Fig 11

Across each condenser C_2 is connected a small 20 µµf trimmer for the purpose of matching the upper and lower plate outputs. This is necessary for two reasons:

(1) it is essential that the girder is brought to the potential of its surroundings, but any asymmetry in the positions of the collecting plates with respect to a horizontal plane through the girder, would cause the two outputs to differ when the mill potential is correct; the trimmers can put this right;

(2) although the nominal value of C_2 is 200 µµf, there may be as much as 5% error in this value and also the connecting cables may differ slightly in capacitance.

A further reason for the outputs differing, when the girder potential is correct, may be that the surfaces of the collecting plates and rotors may differ from one pair to the other, giving different outputs from contact potentials. The use of polished stainless steel reduces this effect, but Whitlock (1955) found that it might be equivalent to a potential gradient of ± 10 v/m.

5·2. Cathode Followers, Amplifiers and Power Supplies.

We have already discussed [para. 4·1] the need for cathode followers to match the high mill output impedance to the low impedance of the cables connecting the mill and the amplifier, and to isolate this high cable capacitance from the necessarily low mill capacitance. The circuit is shown in Fig. 9; two identical units were constructed, sealed in waterproof boxes and mounted half-way up the supporting posts; this position decreases the maximum length of the cable between the junction box and the cathode follower and allows the mill to be moved to its highest and lowest positions [see Fig. 19].

The cathode followers were tested for equality of response between input values of 0 - 10 v. at the mill frequency of 200 c.p.s. and were found to be equal to within 1% with a stage gain of 0·71.

Fig. 11 shows the circuit diagram of the potential-gradient amplifier used. This amplifier employs negative feedback over both stages to give added stability and to render the overall amplification factor independent of variation in the supply voltages, changes in the values of circuit components with temperature or time and alteration of the valve characteristics with aging. An input selector is placed across the secondary of the input transformer giving input fractions of 1, 1/2, 1/5, 1/10, 1/50 and 1/100.

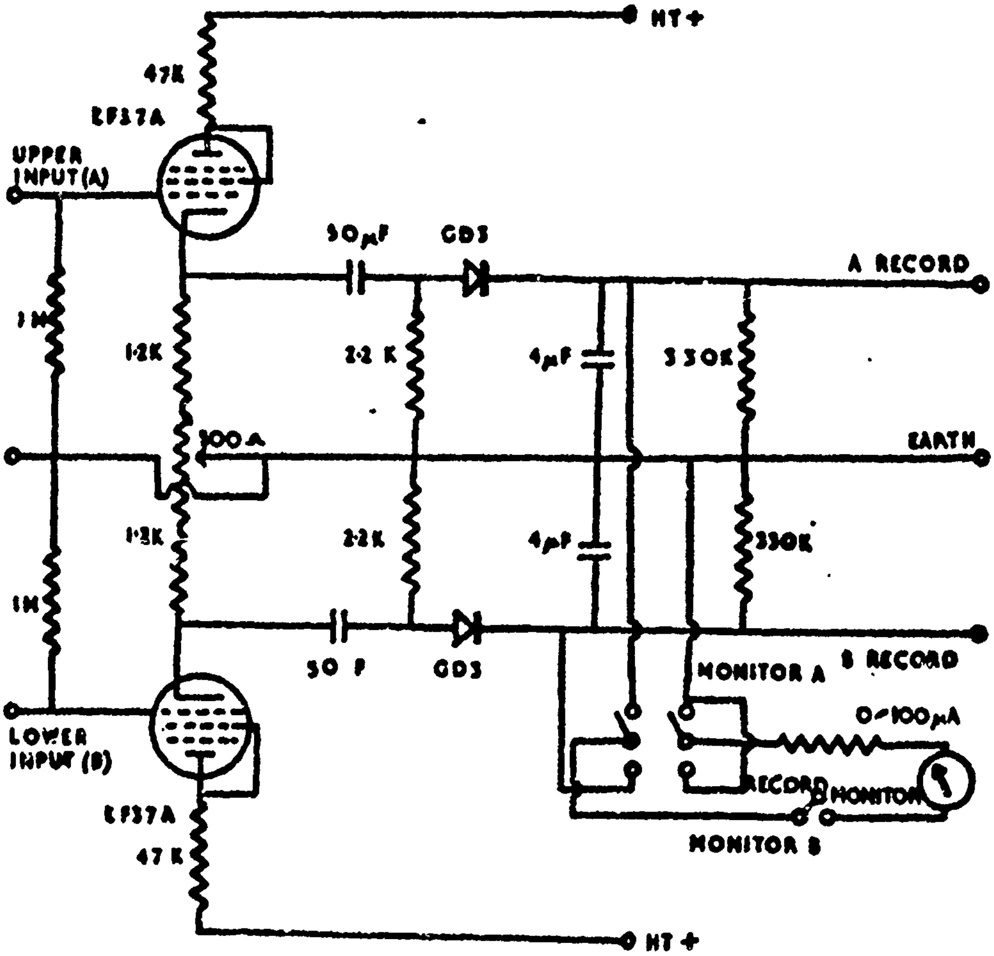

HT+
47K
EF37A
UPPER INPUT (A)
50μF
GD3
A RECORD
1M
1·2K
2·2 K
4μF
330K
100 A
EARTH
1·2K
2·2K
4μF
330K
1M
50 F
GD3
B RECORD
MONITOR A
0-100μA
LOWER INPUT (B)
RECORD
MONITOR
EF37A
47 K
MONITOR B
HT+

Fig 13

The fraction, β, of the output voltage fed back is given by:

$$\beta = \frac{R_2}{R_1 + R_2}$$

If A is the amplification without feedback, then the voltage amplification, A_F, with feedback is

$$A_F = \frac{A}{1 - A\beta} = -\frac{1}{\beta}\,\frac{1}{1 - 1/A\beta}$$

If $A\beta >> 1$, then $A_F = -1/\beta$ and is independent of the amplifier characteristics.

In the present case, the amplification of the first stage is 176 and of the second stage 140, R_1 is 36·5k, and R_2 is 1k

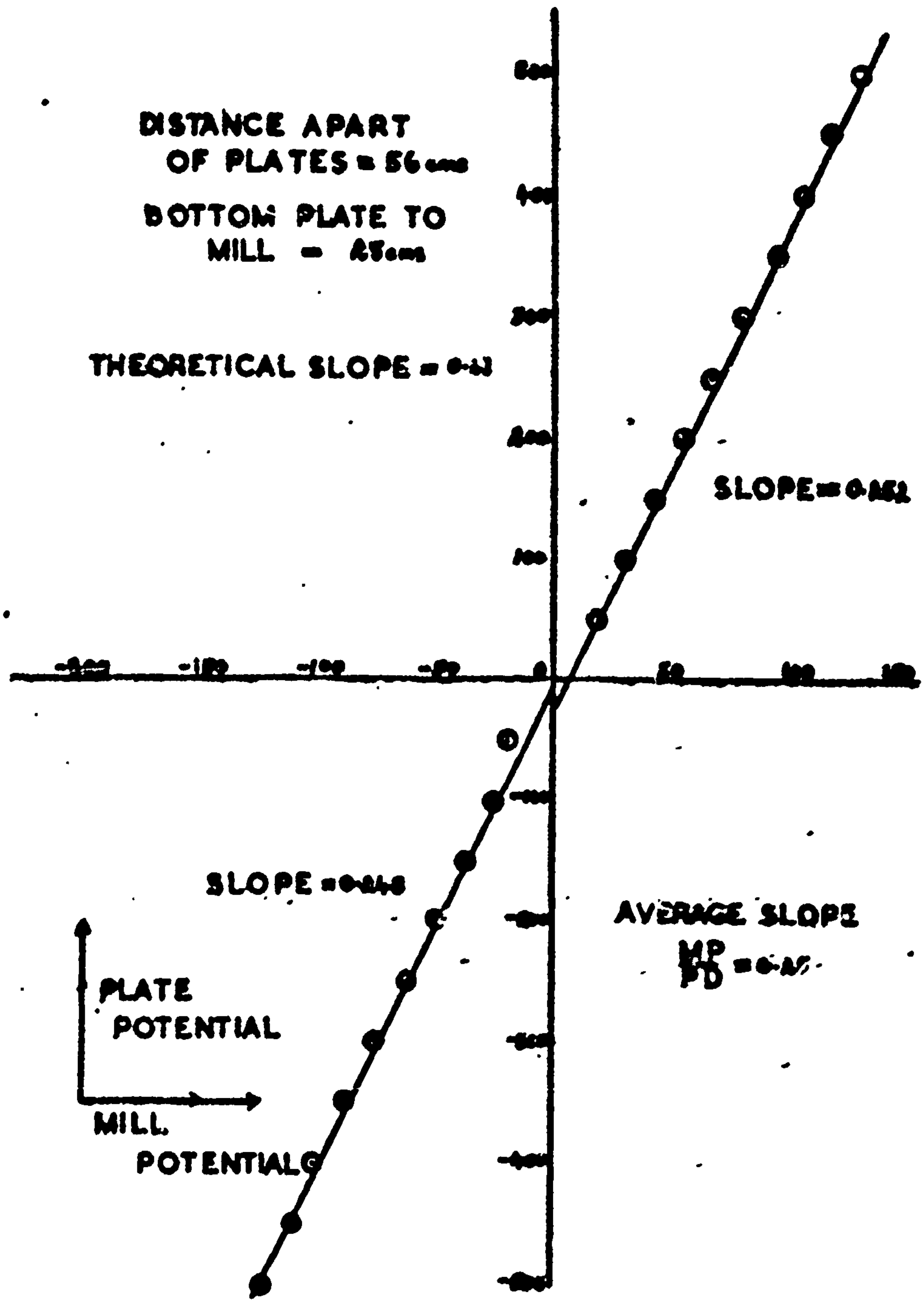
$\therefore$ $A = 24{,}640$ and $\beta = 1/37{\cdot}5$, so that $A\beta >> 1$ and $A_F = -37{\cdot}5$.

The amplifier was tested at mill frequency, using the "1" value for the input selector, and showed a linear response up to 1 volt input with an amplification of 86·3, showing a ratio of 2·3:1 for the input transformer.

A second similar amplifier was built and tested, and was made to have an identical response by adjusting R_1 slightly. The amplifiers were built onto a common 10" x 17" duralumin panel, so that all the electronic gear could be mounted in a standard rack, thus being easily accessible. The two input selector switches were "ganged" to the same control to avoid the possibility that they might be left at different positions.

The power supply was stabilized at 350 volts, using Neon Osram STV 280/40 "Stabilivolt" tubes and supplied a total of four amplifiers, two to each double mill. A subsidiary tapping from the same supply gave a voltage from 0 to 140 volts for the cathode follower. Investigation of the output at varying load currents showed a variation of only 0·8 volts with currents up to 33 ma, though above this value the output falls off rapidly; in use, the total current is only about 28 ma, so the power supply is operated within the regulated limits.

Because of the high output impedance of the amplifiers, it was thought necessary to feed the amplified outputs into the following stages through cathode followers. For this purpose, it is not necessary to run the valve at reduced heater and anode potentials, because the value of the grid current is not important here. The circuit diagram is shown in Fig. 13; the valves used are Mullard EF 37A, with a 500Ω potentiometer between the two cathode resistors to provide an adjustment to the relative magnitudes of the two outputs, in addition to the trimmer condensers in the mill output circuits [para. 5·1].



DISTANCE APART
OF PLATES = 56 cms
BOTTOM PLATE TO
MILL
THEORETICAL SLOPE
SLOPE
SLOPE
AVERAGE SLOPE
PLATE
POTENTIAL
MILL
POTENTIAL

Fig 16

Thus all adjustments to make the amplifier responses equal can be made with this 500 Ω potentiometer.

After rectification with a Germanium diode rectifier GD3, the upper and lower plate outputs are fed, in opposition, to the servo-motor and in addition the upper plate output is taken through a high resistance recording galvanometer to earth for the purpose of recording the potential gradient. The resistance of the galvanometer is sufficiently high so as not to upset the balance of the outputs.

A subsidiary monitoring circuit is incorporated in the cathode follower stage to provide a visual check of potential gradient values; this may be switched into either upper or lower plate output, or removed from the circuit when recording. A test of the amplifier and cathode follower was made and showed an overall amplification of 22·6; comparison with the value of 86·3 for the amplifier alone shows a considerable loss through the cathode follower and rectifier stages. The response tails off for inputs below 7 mV, using the value "1" of the input selector, indicating that the rectifier has a non-linear characteristic in this region; the mill-amplifier system therefore needs to be calibrated.

It is convenient at this point to calculate the expected magnitude of the rectified output in terms of the potential gradient.

From the equation of para. 4·1,

$$V = F \times 1{\cdot}4 \times 10^{-4}[1 - 7{\cdot}7 \times 10^{-2}] \text{ volts;}$$

the stage gain of the mill cathode follower is 0·71 and of the whole amplifier 22·6. Assuming no loss in the mill blocking condenser and in the cables, the final result is

$$V = 2{\cdot}07 \times 10^{3} F \text{ volts}$$

i.e. a potential gradient of 1 v/m should give a final output of 2 mv.

To investigate the behaviour of the system under balancing conditions, two horizontal aluminium plates 1 m. square were set up 56 cm. apart. The mill was placed with its centre 23 cm. above the lower plate and the lower plate earthed. The upper plate was given a potential of -50 volts and the mill -20·5 volts, the correct value for its position; the 500 ohm potentiometer was then adjusted until the two outputs from the mill were equal. Then different potentials were applied to the upper plate varying between ± 500 v, and the corresponding mill potential found, so that the two outputs became equal.

The results in Fig. 16 showed a good straight line, except for the value for -50 volts, so that the potentiometer setting was incorrect; this deviation may have been caused by charges on the mill driving belt. In consequence of this, the slope of Fig. 16 is 0·25 and not the theoretical value of 0·41. However, it is clear that the double mill does function as desired.

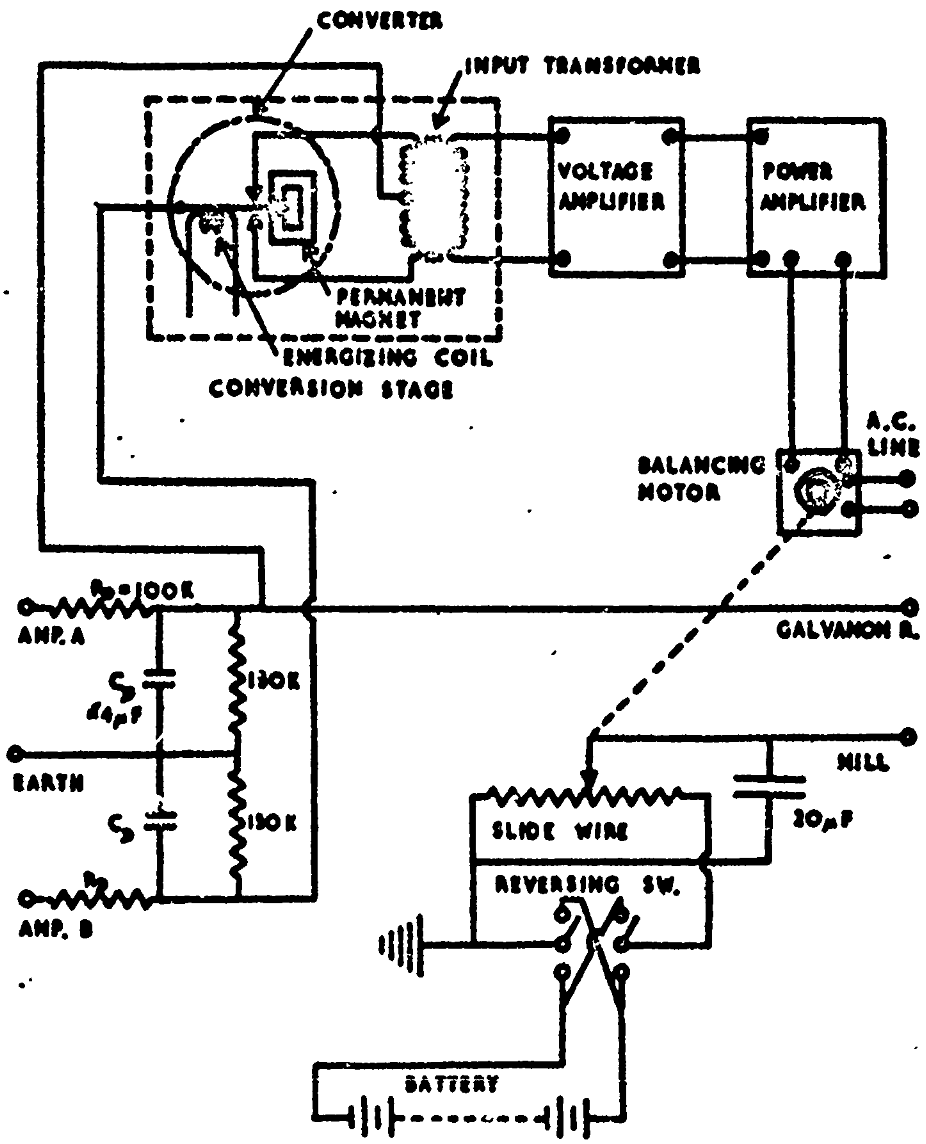

CONVERTER
INPUT TRANSFORMER
VOLTAGE AMPLIFIER
POWER AMPLIFIER
PERMANENT MAGNET
ENERGIZING COIL
CONVERSION STAGE
A.C. LINE
BALANCING MOTOR
GALVANOM R.
AMP. A
130K
EARTH
130K
AMP. B
MILL
SLIDE WIRE
20μF
REVERSING SW.
BATTERY

Fig 18

It was also found that the sensitivity of the whole system is 2·0 mv per v/m as predicted and falls off at low potential gradients.

For space-charge measurements, a second field mill is required, and, as the commutator system had been abandoned, the second mill was constructed without this, allowing the overall height to be reduced to 14 cm. The vane shaft and driving shaft were mounted in a duralumin rectangular block, cast for the purpose and making a neater job than the motor casing used in the first mill. Apart from this, the equipment for the second mill was identical with that for the first.

5·3. Potential-Balancing Servo-Mechanism.

The instruments used for the purpose are Honeywell-Brown "Continuous Balance" Electronic Chart Recorders; the original use of these instruments was to balance a standard potential placed across a slide-wire against the voltage generated by a thermo-couple and thus to measure a temperature. The difference between the slide potential and the thermo-couple potential in an unbalanced position is fed into a two-stage D.C. amplifier and then actuates the motor driving the slide to a balance position, this position being registered on a moving chart by a pen attached to the slide. The sensitivity of the amplifier may be varied, the motor responding to a minimum change in input of 0·03 mV at maximum sensitivity. The time of travel of the slide from zero to full-scale position is 12 sec. and the chart speed may be varied from 30 to 120 in./hr.

For the present purpose, the instrument was modified by removing the existing slide wire and circuit and replacing it with a slide wire of resistance 1 M. This consisted of a row of 8 BA bolts screwed into a Tufnol board having the same dimensions as the original assembly, with the slide running over the heads of the bolts. To the reverse side of the bolts were soldered 100 10 k resistors; the zero end of this chain was connected permanently to earth and the other end, through a reversing switch, to a 600 volt source of 5 HT batteries. The batteries were considered preferable to a power pack running from the mains, because of the difficulty of smoothing the latter sufficiently; a 1 volt ripple at 100 volts would give an output equivalent to an alternating field of 1 v./m.

The slide contacts are insulated from the rest of the instrument, one sliding along the bolt heads and the other along a "collector" wire placed parallel to the resistance contacts. Fig. 18 shows a schematic diagram of the balancing system. The RC circuit across the input is recommended by the manufacturers to render the instrument slightly overdamped;

without the components R and C , the motor oscillated about the balance point with an amplitude of approximately 4% of the full scale deflection, with a perfectly steady input and the amplifier at maximum sensitivity.

Because the slide wire has not a uniform variation of resistance along its length, since it is composed of 10 k steps, the voltage supplied to the mill varies in steps of 6 volts from one contact to the next. This is why the theory in para. 4·4 was worked out for a step voltage applied to the mill and not for a sudden change of potential gradient. Another effect of this discontinuity in the slide wire is to reduce the accuracy with which the voltage is fed to the mill. Investigating the accuracy with which the servo-mechanism will follow a change in potential gradient, it can be shown that if the effect of the 20 μf smoothing condenser (Fig. 18 and para. 4·4) is neglected, with the mill at 1 m. height and a potential gradient of 100 v/m changing at the rate of 1 v/m per minute, the greatest divergence from the true potential is only 1·4%. Taking into account the effect of the 20 μf condenser, which in combination with the slide wire gives a time constant of 20 secs., then the error introduced for this rate of change is less than 1·4%. The faster the change in potential gradient, the lower is the error and as most changes occur faster than the rate given above, 1% represents a fair value of the "tracking error".

5·4. Recording Galvanometer and Time Synchronization.

The Brown Recorders give the potentials of the two mills, registered on their respective charts. For the purpose of recording the potential gradient the output from the upper plate of each mill is taken to a galvanometer.

The galvanometers used were Tinsley moving coil suspension galvanometers, type 4500/10 f, having a periodic time of 2 sec. and a sensitivity of 1500 mm/μA at 1 metre. The coil resistance is 45 Ω and critical damping needs a shunt resistance of 12 k. Three series resistors were used to give suitable sensitivities with the "1" value of the amplifier input selector.

Trial measurements showed that including the Brown Recorder in the circuit reduced the estimated output (para. 5·2) from 2 mv to 1 mv per v/m. The full width of the recording paper used in the camera [240 mm s available because the output is always positive with respe to earth, so a current of 0·16 μa is needed to give full scale deflection. Using resistor values of 1·5, 0·68 and 0·22 M , full scale deflection is obtained with 240, 109 and 35 v/m, corresponding to sensitivities of 1, 2·3 and 6·8 mm per v/m respectively; these will be referred to as "Low", "Medium" and "High" sensitivities.

From the sensitivities just calculated, and using also the various settings of the input selector, a range of ± 24,000 v/m would be covered. However, there are practical limits set by the maximum slide potential available in combination with the height of the mill. With 600 volts on the slide wire, the limits are ± 1,200 v/m at a height of ½ m but only ± 100 v/m at a height of 6 m.

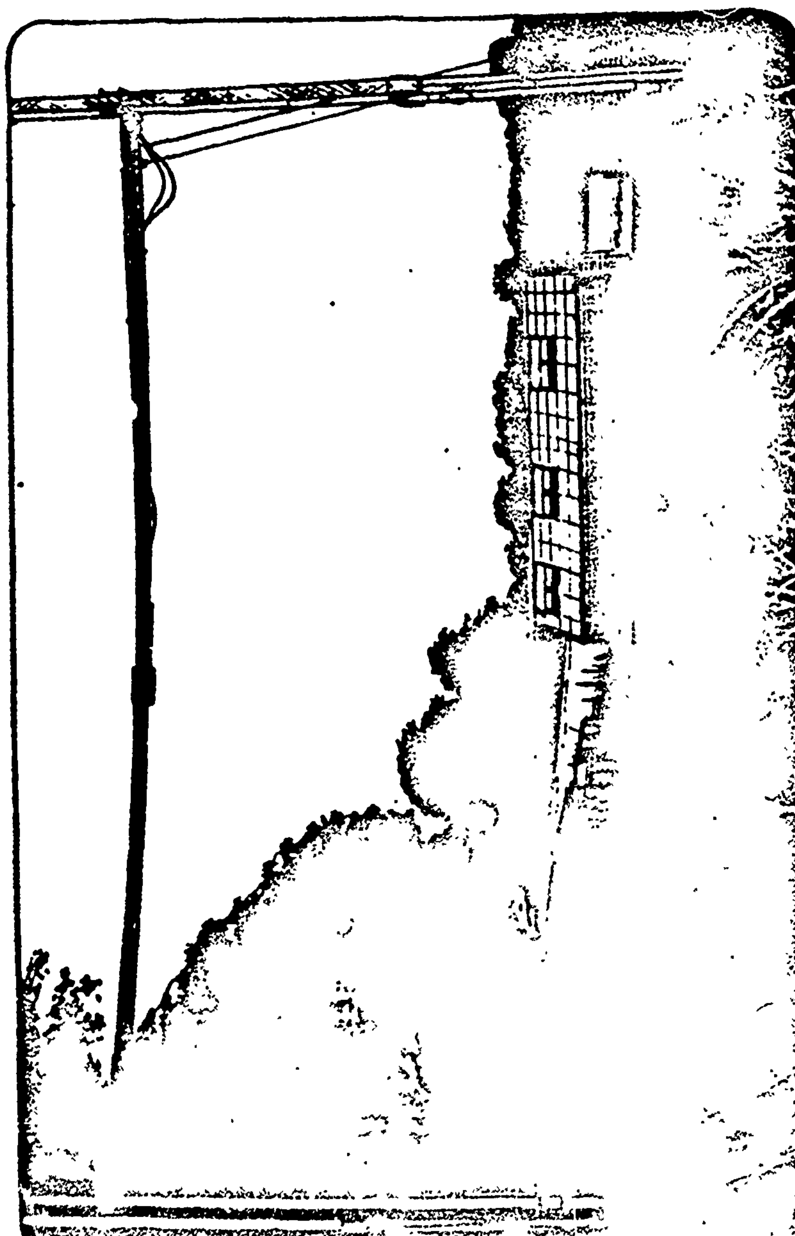
The camera used for recording purposes was made in the laboratory workshops. It was equipped to take a 100 ft. roll of 240 mm. width recording paper and driven by a geared down motor powered from the mains, giving a paper speed of 30"/hr.

In addition to the two Tinsley galvanometers, a third galvanometer was connected to the agrimeter (Chalmers, 1953), giving a useful check on potential gradient values at the earth's surface.

Since recording was being done on photographic paper, a method of obtaining zeroes was needed, and also time marks are needed both on the photographic record and on the Brown recorders. A 50-volt, ½-minute pulse every 5 minutes was available for this purpose. This pulse operated a Post Office 5,000 type relay, with its contacts arranged so that the upper output from each amplifier was earthed for ½ minute every 5 minutes, thus bringing the potential gradient galvanometers to zero and so allowing a zero line to be drawn on the photographic record. In addition, the Brown recorders see this earthing of the upper outputs as a decrease in potential gradient which they attempt to follow; consequently the slide moves down to zero mill potential, giving time marks on the Brown charts. This operation, occurring every 5 minutes, also fulfils the condition stated in para. 5·2, that the mill must start from zero potential when potential gradients are small.

The Brown Recorder charts are graduated laterally in ⅓" divisions, enabling readings to be made at 40 sec. intervals with a chart speed of 30"/hr, and longitudinally into 100 divisions; this would allow a reading to be taken to 1/10 division, i.e. 0·6 volts. For ease of reading off values from the photographic trace, a mm. scale is inscribed on the camera lens, its "shadow" being recorded on the paper by means of a fogging lamp, placed as near as possible to the galvanometers. This lamp was connected to its supply through a second relay worked by the 5-minute interval pulse; this caused the lamp to be switched off at the same time as the galvanometers are zeroed, leaving a white line across the paper. Later, a subsidiary timing circuit was introduced, which interrupted the fogging lamp supply for 2 sec. every ½ minute, giving greater ease of time measurement.

The agrimeter gives both positive and negative deflections and so was zeroed at approximately the centre of the camera scale. It was equipped with its own zeroing and calibrating device; the galvanometer has three sensitivity values: 0·125, 0·0305 and 0·00585 mm. per v/m giving full scale deflection (120 mm) for 960, 4000 and 20,000 v/m.



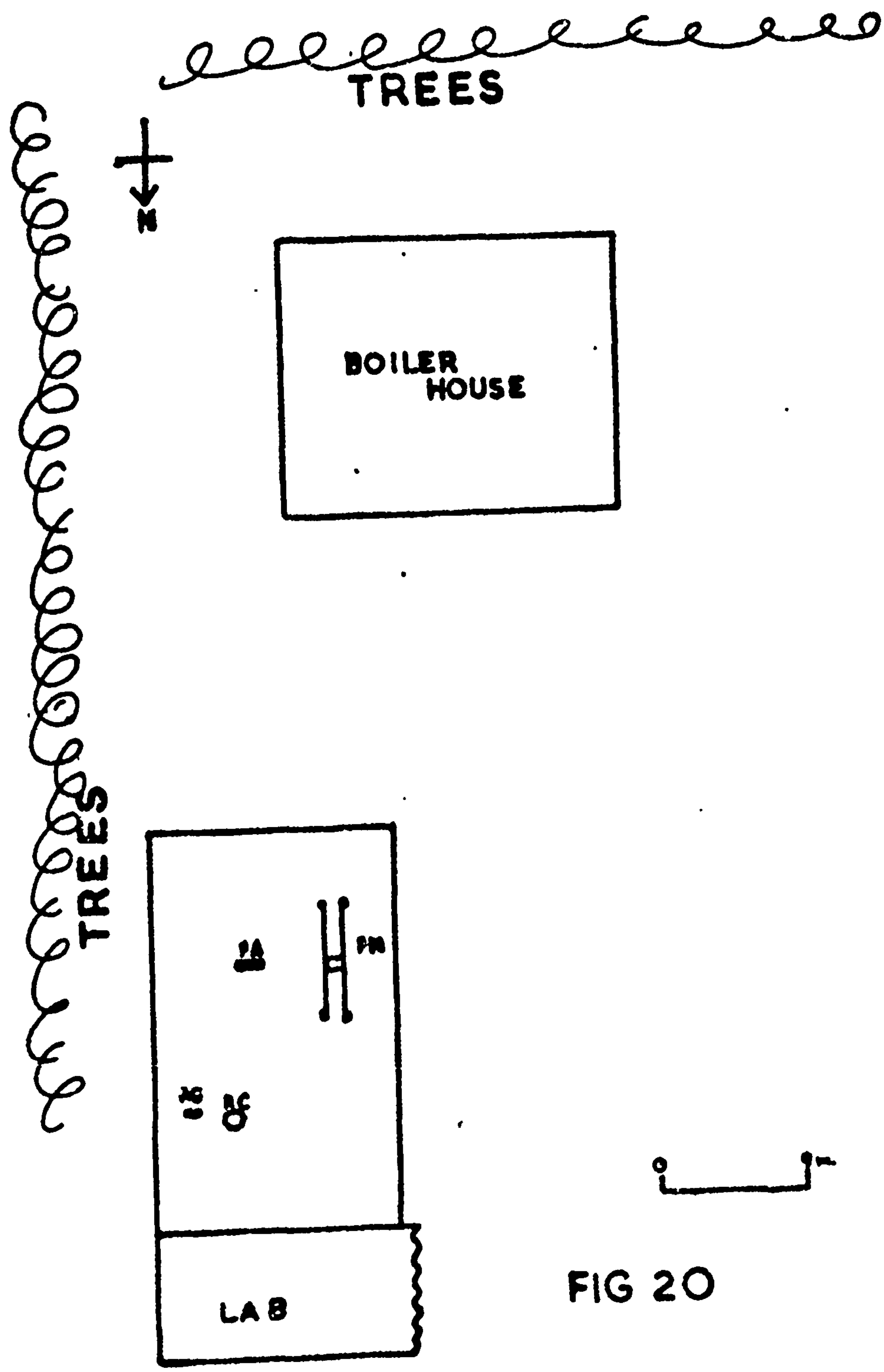


FIG 20

CHAPTER VI. OPERATION AND BEHAVIOUR OF THE COLLECTORS

6·1. The Site and Erection of the Apparatus.

Unfortunately, no choice could be exercised in siting the apparatus, the only site available being that shown in Fig. 20. As can be seen from this diagram, the site is screened on the eastern side by a single line of trees, on the north by laboratory buildings and on the southern side by a boiler house behind which is a large wood. The ground slopes quite steeply upwards beyond the southern fence (shown by a solid line) and, because of this, no direct southerly winds could reach the apparatus. To the west and east, the landscape mainly consists of open meadows and to the north lies the major part of Durham City.

The plot itself slopes gently downwards from south to north, as may be seen from Fig. 19. The mill-supporting posts were erected vertically, and the method employed to fix the Tufnol bars, supporting the mill girders, to these posts necessitated holes being drilled through the posts to take metal pins securing the bars in position; this arrangement can be seen in Fig. 4. The positioning of these holes was such that the mill girder was as nearly parallel to the ground as possible, and were drilled at an angle to the horizontal so that a couple was applied at each end of the girder, tending to turn the mill in an upward direction. This reduced the sag of the girder from 45 cm. in a natural hanging position, to 15 cm. measured vertically at the mill from a line joining the ends of the girders. This "counter couple", although reducing the distortion of the earth vertical field due to the mill girder not being in an equipotential plane, rendered the operation of raising or lowering the mills extremely difficult and although provision was made for altering the height in ½ m. steps from ½ m. up to 5½ m., recordings were made only at 1 m, 3 m and 5 m.

As mentioned in para. 5·2, trouble was encountered with the plastic driving belt picking up charges and giving an undesirable effect. This was eliminated by totally enclosing the mill pulley and the belt for a distance of 1 m from the mill in an aluminium case. Trouble was also encountered in connection with the switching on of the driving motor; this gained its running speed very quickly, and so there was a considerable stretching of the driving belt, which would often fly off the pulleys. This difficulty was overcome by including a "Variac" in the motor power supply, slowly turning it up to the maximum voltage, thus starting the motor less rapidly, with less strain on the driving belt.

An alteration in the height of the mill would entail a fresh driving belt from the motor, which was situated on the ground. To avoid this, a pair of rails was fixed firmly to the ground, parallel to the mill girders, from the foot of the posts to a distance of 2 m outside them; the motor could then be moved along the rails when the mill height was altered until the belt became sufficiently tight.

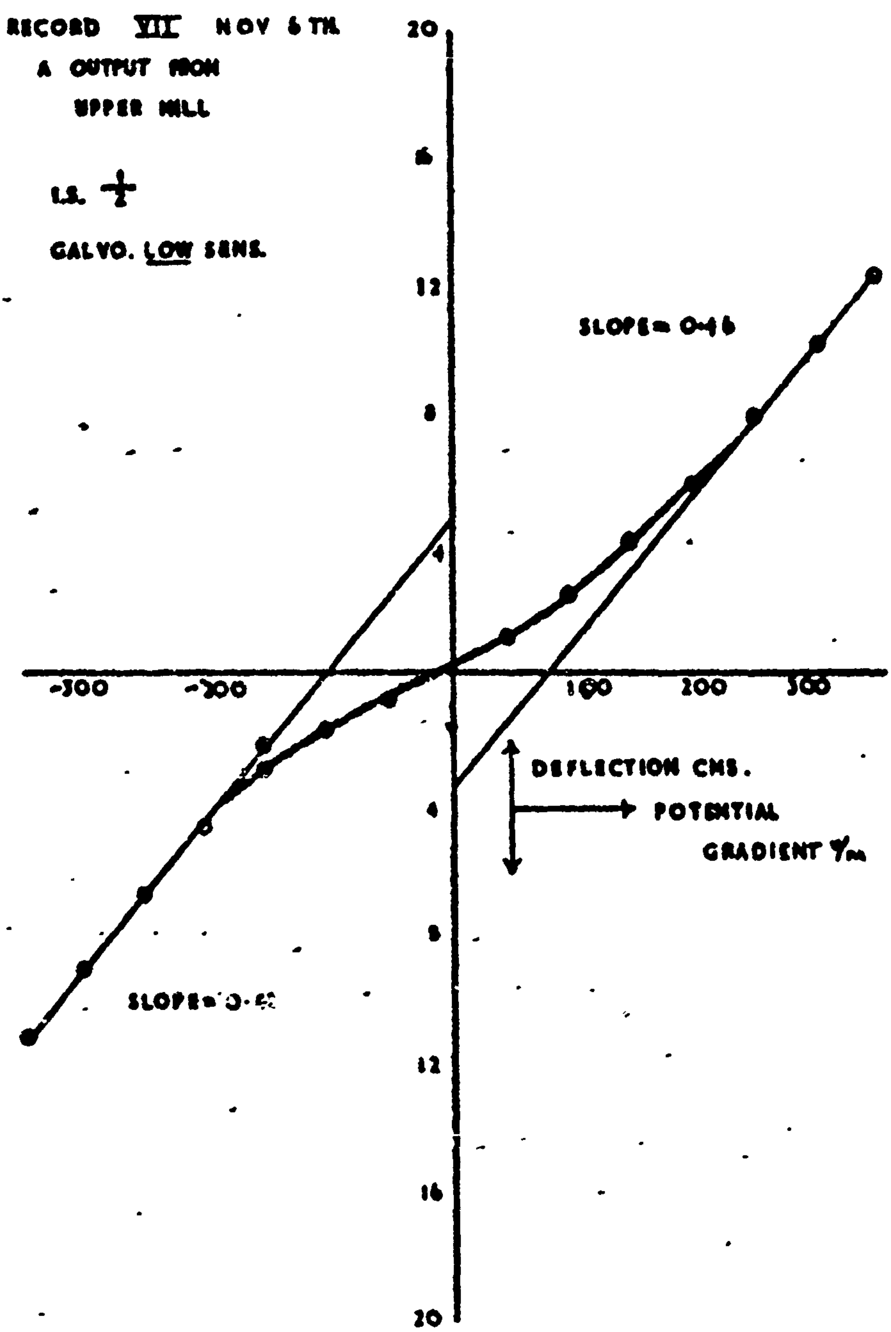
The space charge effects that may be obtained due to the location of the site depend upon wind direction; effects of potential gradient and of disturbances due to precipitation will not be considered yet. With westerly winds, short bursts of space charge may pass over the site from passing locomotives, the railway being about 1¼ miles away; this effect was noticed by Whitlock (1955) in potential-gradient measurements. Also vehicles passing along a road 400 yards away might give space charge effects, but these might be of too short duration to be detected. With northerly winds, the observed space charge may again be artificial, this time due to smoke coming from domestic fires in Durham City; this would probably blanket out any effects due to traffic on a road 300 yards to the north. With winds from the east and south, no peculiarities should be expected until the potential gradient reaches values sufficient for point discharge to occur at the trees [probably about 800 v./m at the ground]; from the trees to the east it is unlikely that point-discharge ions will travel to the region between the field mills, but this may occur in connection with the trees to the south.

On Fig. 20 are also shown the position of the agrimeter at a horizontal distance of 14 m, the rain current measuring instrument RC at 13 m and an Obolensky-type filtration apparatus FA at 5 m.

6·2. Field Operation.

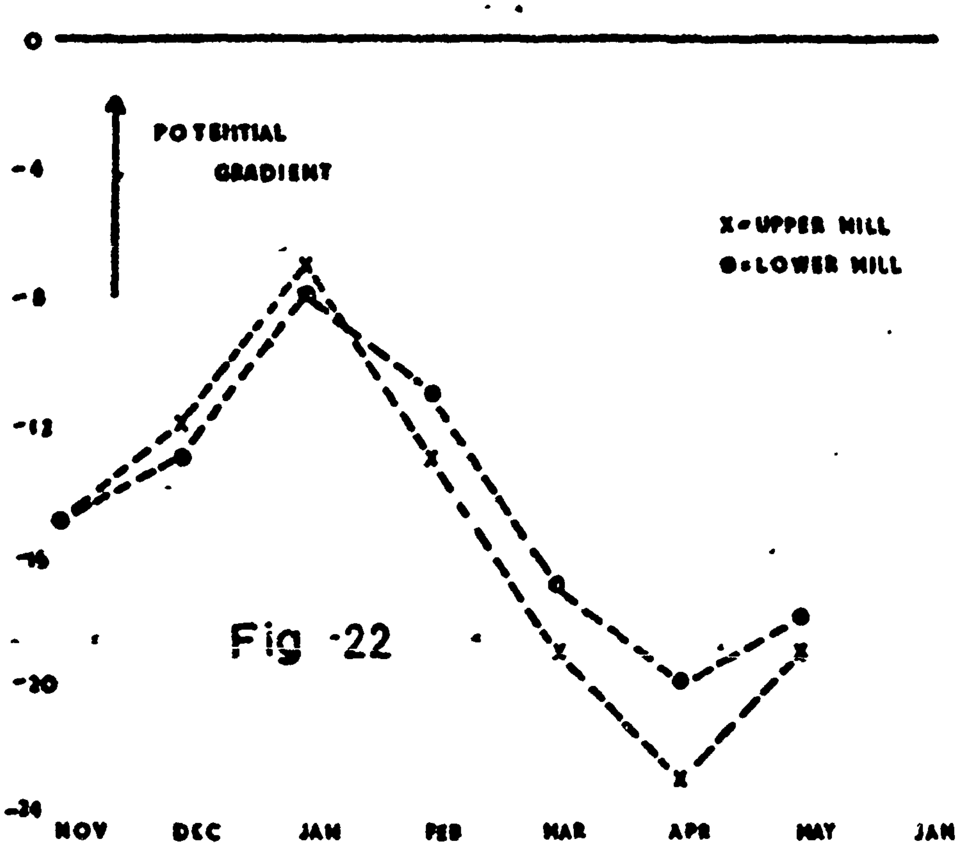
For the purpose of performing an initial calibration, setting the 500 Ω ratio control and testing the accuracy of the mill potential set by the Brown Recorder, the plates used in the laboratory tests were set up around each mill in turn; the lower, earthed, plate was laid on the ground and the second plate set up 70 cm. above this, with the mill in its nominal "½ m" position, i.e. at 35 cm., in the centre of the plates. A variable potential was applied to the upper plate and the mill allowed to balance automatically; to avoid the difficulty experienced in the indoor tests (see para. 5·2) where the 500 Ω ratio control was wrongly set, the maximum potential was applied to the plate and the ratio control set so that the mill potential was exactly half the plate potential. Using a negative instead of a positive potential gave exactly the same setting, showing the correctness of the setting.

The "dead zone" of the Brown Recorder, i.e. the minimum change in potential gradient required to produce a corresponding change in mill potential was found, as expected from the 6 v steps, to be ± 3 v, when the potential gradient was over 100 v/m.



RECORD VII NOV 6TH
A OUTPUT FROM
UPPER MILL
I.S. 1/2
GALVO. LOW SENS.
SLOPE= 0·46
SLOPE=
20
16
12
8
4
4
8
12
16
20
-300
-200
100
200
300
DEFLECTION CMS.
POTENTIAL
GRADIENT V/m

Fig 21



0
-4
-8
-12
-16
-20
-24
POTENTIAL
GRADIENT
X=UPPER HILL
O=LOWER HILL
NOV
DEC
JAN
FEB
MAR
APR
MAY
JAN

Fig -22

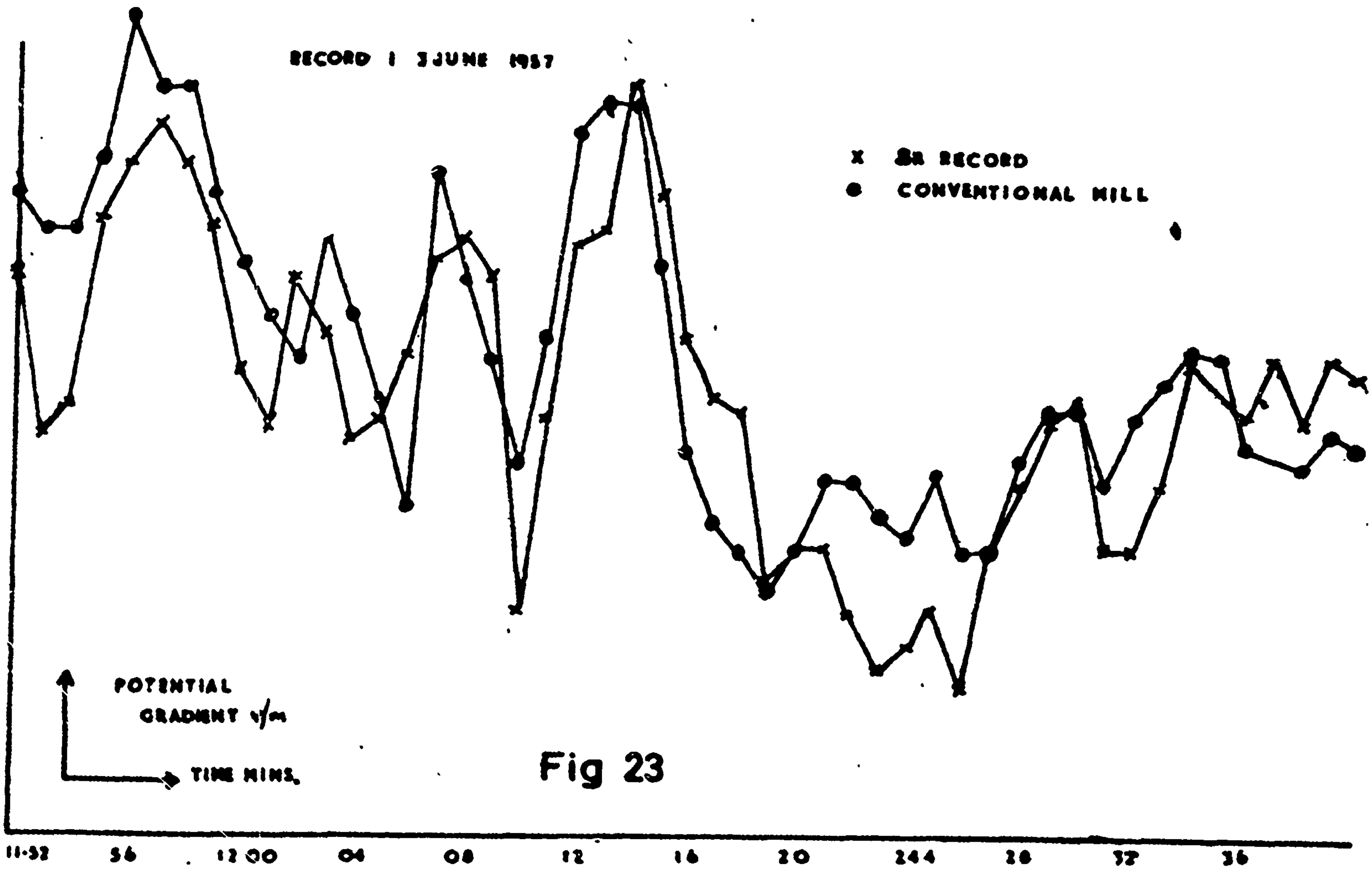
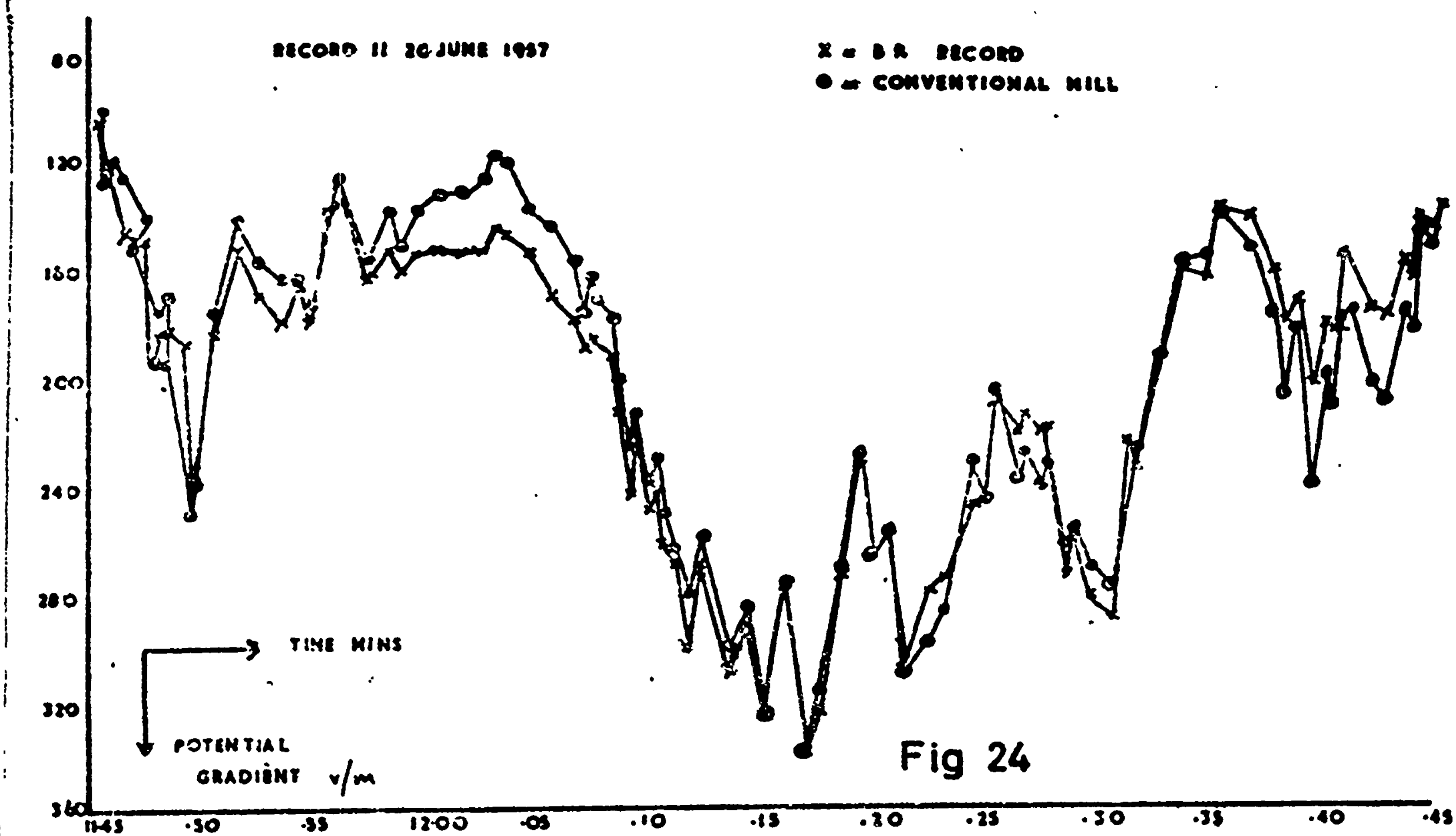

RECORD I 3 JUNE 1957
x RECORD
● CONVENTIONAL MILL
POTENTIAL GRADIENT v/m
TIME MINS.
11·52
56
12 00
04
08
12
16
20
24
28
32
36

Fig 23



RECORD II 20 JUNE 1957
X = B R RECORD
● = CONVENTIONAL MILL
TIME MINS
POTENTIAL GRADIENT v/m
80
120
160
200
240
280
320
360
11·45
·50
·55
12·00
·05
·10
·15
·20
·25
·30
·35
·40
·45

Fig 24

Because of the tail off in amplified response, the dead zone in the region of zero potential gradients is ± 25 v/m.

When the calibration curve was drawn it was found to consist of straight line portions giving intercepts of ± 90 ± v/m and a curved portion passing through the origin. The test plates were similarly set up on either side of the second mill, in order to set the ratio control.

For regular calibrations periodically, a small calibrating plate was constructed from aluminium to fit closely over the top or bottom of each double mill in such a way that it was parallel to the mill vanes at a distance of 3 cm. from the stator. The potential for this plate was supplied from batteries fixed to its outer surface, so that a potential gradient between ± 600 v/m could be applied in 50 v/m steps. Calibrations were made of both outputs of each mill from November 1957 to May 1958 at monthly intervals. One such calibration, that of the upper output of the upper mill, is shown in Fig. 21; apart from a zero output, this is identical to ± 1 mm. with the calibration curve obtained from the two large plates, with the same falling off of sensitivity at low potential gradients to be ascribed to the behaviour of the Germanium rectifier (para. 5·4).

The zero output is probably mainly to be ascribed to the aluminium plate, since when this was replaced by a steel plate the zero output altered from 15 v/m to 2 v/m. A graph of monthly measurements of the zero output is given in Fig. 22; the two outputs from the same mill remained identical and it is difficult to understand why there should be the differences between the two mills.

The upper mill was placed outdoors in June 1958 in a "1 m" position, and the other mill in September. During the time when only one mill was operating, the potential-gradient recording galvanometers had not yet been installed, but on several occasions chart recordings were taken and the values compared with a conventional field mill situated in the plane of the earth's surface at RC (Fig. 20). A typical fine-weather recording is reproduced in Fig. 23 where the agreement between the potential gradient at the ground and that calculated from the potential at 85 cm is quite good, considering that the two instruments are 13 m. apart. The mean potential gradient up to 85 cm is lower, on the average, than the potential gradient at the ground; this gave an average space charge of + 110 $\mu\mu c/m^3$, with an average potential gradient at the ground of + 91·6 v/m.

A recording made in light steady rain is shown in Fig. 24, with a negative potential gradient, higher than in the last case. Here, again, a positive space charge of an average value of + 50 $\mu\mu c/m^3$ is found. During this period, measurements were made of the rain current at RC showing an average positive rain current with a maximum between 11·57 and 12·08, when the space charge was also positive and negative values after 12·35 when the space charge was also negative.

6·3. Behaviour in Rain.

The field mills behaved well even in the strongest rain, though the output became a little "grassy" due to splashing on the vanes. However, in two ways, rain caused trouble.

The Tufnol insulating bars for the mill girder sometimes collected sufficient water on their surfaces to short the girders to earth through the junction box covers, which are mounted on these insulators. This effect became apparent immediately by the Brown Recorders suddenly becoming unstable, due to the reduction of the time constant. The situation was restored to normal simply by wiping the surface moisture off the insulators.

Large charged drops of water falling from the upper mill impinged directly on the upper vanes of the lower mill, giving such a shock to the Brown Recorder that it required up to 10 sec. to return to its balance point. In medium or strong winds, this effect does not occur, as the drops are blown clear, but with light winds and heavy rain, a balance point was sometimes impossible for the lower mill. A temporary cure could be affected by pushing the upper mill to one side, but it would soon return to its normal position and the difficulty would recur; in these circumstances, recording would be abandoned. This effect might perhaps be removed by offsetting one mill with respect to the other along the girder length.

6·4. Recording Procedure and Record Analysis.

At the commencement of a recording session a five-minute running period was allowed for the paper in the camera to tighten and settle down to a uniform speed. During this period, the mill insulators were checked by observing the rise in potential of each mill when 600 volts was applied to the Brown Recorder slide. The sign of the potential gradient was established either by reference to the agrimeter or by switching on the Brown Recorder and noting the direction of drive of the slide. If it showed no tendency to drive upwards with either positive or negative voltage on the slide wire, and could be set in any position, then the potential gradient was less than 25 v/m (with the input selector at ½) and recording was abandoned.

When the two Brown Recorders were balancing, a value of the input selector for each mill was chosen to give a reasonable deflection of the potential-gradient galvanometer; the galvanometer sensitivity adjustment was seldom used, remaining at "Low" for the majority of recordings; the Brown Recorder sensitivity was then adjusted such that the slide was just below the point of responding to potential-gradient changes of the order of period of 2 sec.

After completion of these checks, the time of the next ½ min. extinction of the fogging lamp was noted, together with the sign of the potential gradient on each Brown Recorder chart, and the record considered to begin at this point. During the whole recording, note was taken of the strength and direction of the wind, times of change of sign of potential gradient, precipitation details and the state of overhead cloud.

We have already discussed (para. 5·4) how timing and zeroes are indicated both on the Brown Recorder and photographic records. The thickness of the photographic trace is about ½ mm, and measurements were made to the nearest mm, corresponding to 1 V/m for an input selector value of "1" and "Low" galvanometer sensitivity. On the Brown Recorder, no advantage accrues from any attempt to read to better than ± 3 v, since this is the "step" change. To distinguish between upper and lower mill traces on the photographic recording, the galvanometer zeroes were set 1 cm apart and, in addition, the upper mill galvanometer lamp was slightly offset to give a fainter trace.

There is a choice of 3 methods of reading off values from the traces:

(1) Values at "major features", e.g. maxima and minima,

(2) Average values over minute intervals,

(3) Instantaneous values at minute intervals.

The first method would, in some cases, give very few readings. The second method is difficult to apply when there are rapid fluctuations. The third method, though sometimes missing rapid potential-gradient changes, is simpler and probably more accurate, and this was used in analysis.

From the analysis of a record, it is possible to obtain, at each minute, the potential at each mill, the potential gradient at each mill and, from the agrimeter record, the potential gradient at the ground. From these readings, it is possible to get the average space charge between the two mills from the potential gradients; a check using mill potentials usually agreed to within ± 10 $\mu\mu c/m^3$. The average space charge below the lower mill can be found from the lower mill potential gradient and potential, or from the mill potential gradient and agrimeter reading; these two results do not always agree because: (1) the effective sampling height is different, (2) there is a horizontal separation of 14 m and (3) the agrimeter has a long response time.

CHAPTER VII. APPARATUS FOR FILTRATION METHOD

7·1. Apparatus.

With apparatus in operation to measure the space charge from the potential-gradient change, it was thought desirable to construct, also, apparatus to measure the space charge directly, so that a comparison could be made. If suitably constructed, the latter apparatus would not record the actual charge on the precipitation, but this would be included in the results from the change of potential gradient.

An Obolensky-type filter was constructed along the same lines as that made by Kinman ('i). This consisted of an insulated brass cylinder packed ..ightly with fine steel wool and effectively screened from any effects of variation in potential gradient by enclosing the cylinder inside a brass box. The air inlet was shielded to prevent any possibility of precipitation entering the inlet or splashing in the near vicinity to give spurious effects.

Air was drawn through the filter by a motor driving an old "Hoover" fan unit; this motor was driven by the mains through a "Variac", enabling the air speed to be varied up to 0·6 litres/sec. The suction motor was connected to the air filter by 6 m. of flexible rubber hose and a reservoir interposed between the two to smooth out small changes in the rate of air flow, caused by short-period variations in mains voltage. The purpose of using the long length of hose was to enable the suction motor to be moved down-wind of the filter, ensuring that the air expelled from the motor would not re-enter the filter, nor would the latter pick up any charges which might be generated at the motor brushes. To eliminate variations in air flow which might arise from changes in wind speed, the motor outlet and filter inlet were made to face in the same direction.

For the measurement of the charge collected by the filter an EKCO Vibrating Reed Electrometer (VRE) Type N 572 was used. To avoid piezo-electric effects, the "Head Unit" was bolted to the screening case of the filter and a direct rigid connection was made from the collecting cylinder to the input terminal. With the input resistor of 10^{12} ohms, the electrometer on its most sensitive range has a sensitivity of 0·03 $\mu\mu$a for a full-scale deflection.

After calibration and testing had been carried out in the laboratory, the filter was mounted at F.A (Fig. 20) at a distance of 5 m. horizontally from the double field mills. The air inlet was set facing west at a height of 65 cm. above the ground; this made the highest point of the apparatus 80 cm. above the ground. Applying Benndorf's criterion (see para. 4·2), this apparatus affects the potential gradient at the double mills by less than 1%.

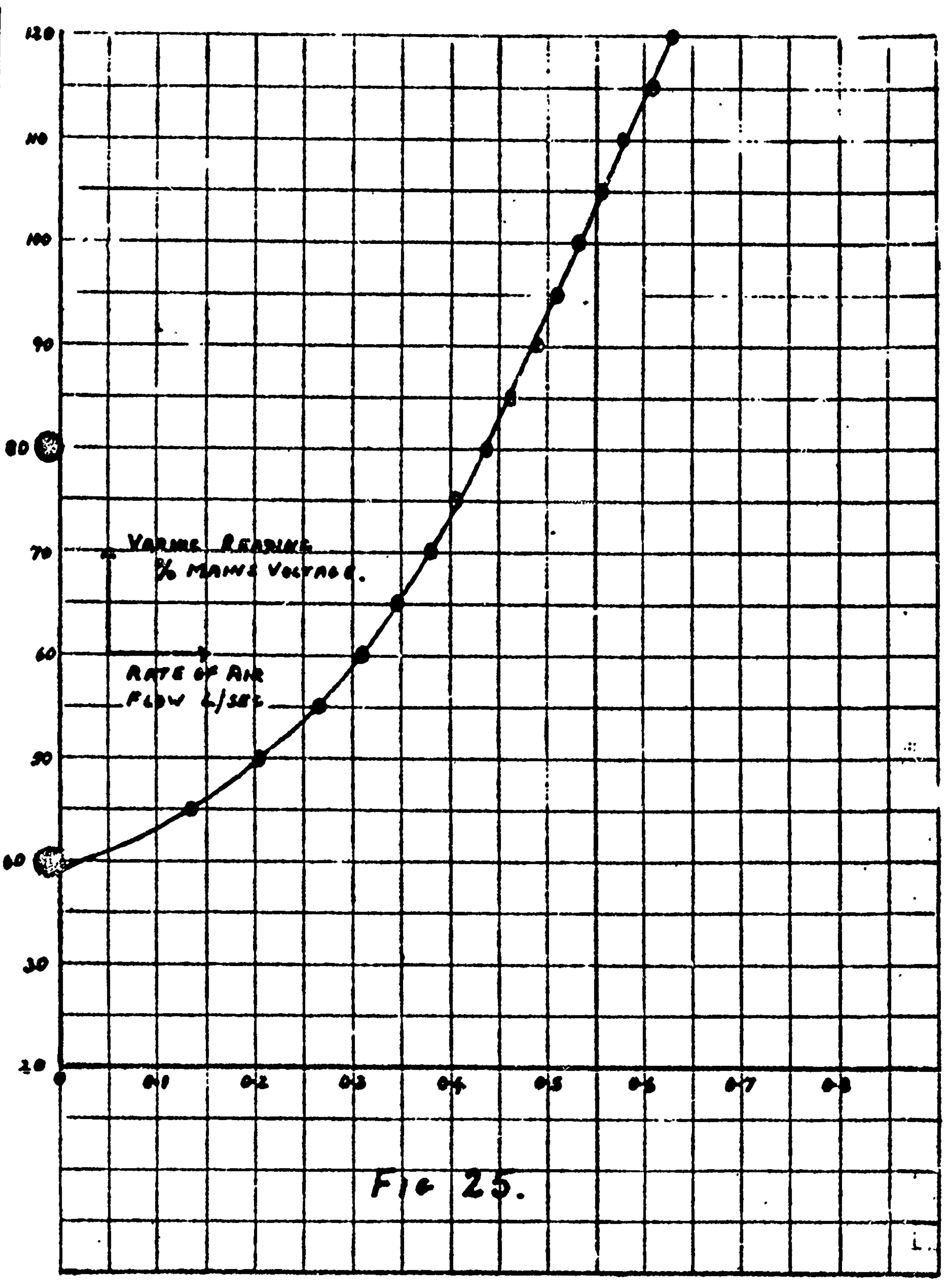

120
110
100
90
80
70
60
50
40
30
20
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
VARIAC READING
% MAINS VOLTAGE.
RATE OF AIR
FLOW L/SEC

FIG 25.

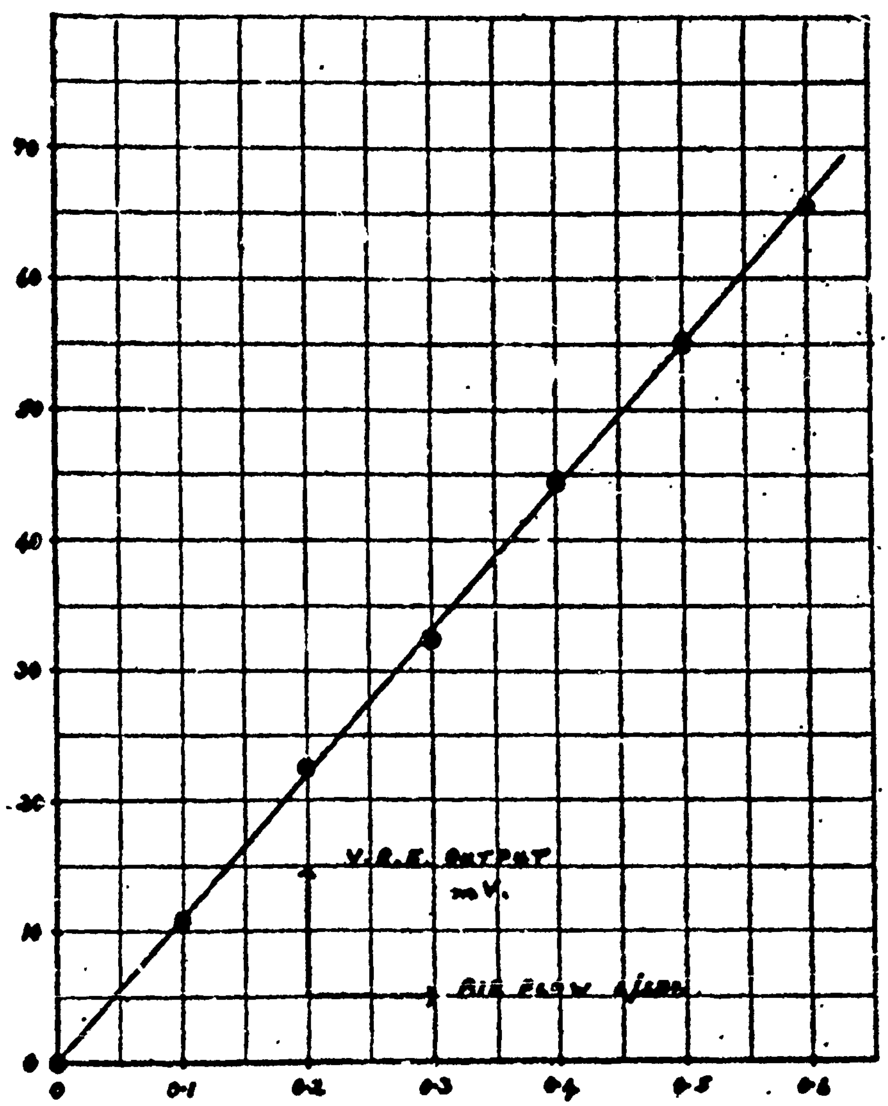


FIG. 26.

7·2. Calibration and Testing.

For the purpose of recording the VRE output, a Nivoc suspension type galvanometer was set up to give a photographic trace on the camera. The galvanometer was arranged to give a full-scale deflection of 12 cm. for a current to the VRE of 0·02 µµa.

For testing, the filter was set up inside a small room, with the suction motor outside, connected by the rubber hose to the filter; this precluded any air already sucked through from being drawn into the filter again.

A 4" anemometer was mounted close to the filter inlet and a calibration curve obtained of the air flow through the filter against the setting of the Variac, which controls the voltage and hence the speed of the motor. The results, verified on 3 occasions, are shown in Fig. 25.

After removing the anemometer, a test was then made to relate the air flow and the VRE output. To provide a constant space charge, a smouldering piece of string was placed in front of a fan which produced a uniformly distributed smoke cloud in the room; the door was left slightly open so that the concentration of the smoke remained constant. It was verified, by 5 minutes running at the same air flow and by repeating the measurement 10 minutes later, that the space charge remained the same. The linear variation of VRE output with air flow is shown in Fig. 26. The corresponding space charge is + 110 µµc/m³.

In order to obtain a zero reading for the filter, the suction motor was switched off and it was verified that this agreed with the VRE zero.

CHAPTER VIII. RESULTS IN FAIR WEATHER

8·1. Introduction

Fair weather is defined as comprising periods during which no precipitation reached the ground and during which the potential gradient remained within the range 0 - +400 v/m. This last condition excluded cases of mist and fog.

In many cases, the potential gradient traces showed variations corresponding to 10 - 20 v/m in a few seconds. In taking values at minute intervals, the mean of such variations was taken, involving a possible error of ± 2 v/m, which would be much reduced on taking statistical averages.

If F_u and F_L are the potential gradients at the upper and lower mills respectively, then the mean value of the space charge over the height range h is given by:

$$\rho = \frac{\epsilon_0(F_L - F_u)}{h}$$

This value is referred to as ρ_{1-3} or ρ_{1-5}, according as the height of the upper mill is 3 m or 5 m (nominally), that of the lower mill remaining at 1 m (nominally). The actual heights are 15 cm. lower than the nominal heights.

In a few cases, the space charge between the ground and the lower mill was obtained, either by using potential gradient values from the lower mill and the agrimeter, or by using both the potential gradient and the potential of the lower mill. These values are referred to as ρ_{0-1}, with the instruments referred to if necessary.

In discussing results, the actual records will not, in general, be reproduced because of the difficulty of interpreting them simply at sight. Instead, the calculated values of space charge are plotted, together with the average potential gradient close to the ground, obtained from the balancing potential of the lower mill.

8·2. Effects of Wind Speed and Direction.

In fair weather conditions, unless the wind speed is extremely low, space charges, even on small ions, are transported more by the wind than by electrical effects. It is therefore reasonable to expect that the space charges will pass overhead with the wind velocity and therefore that their effects will increase in frequency and possibly also in amplitude with increasing wind speed.

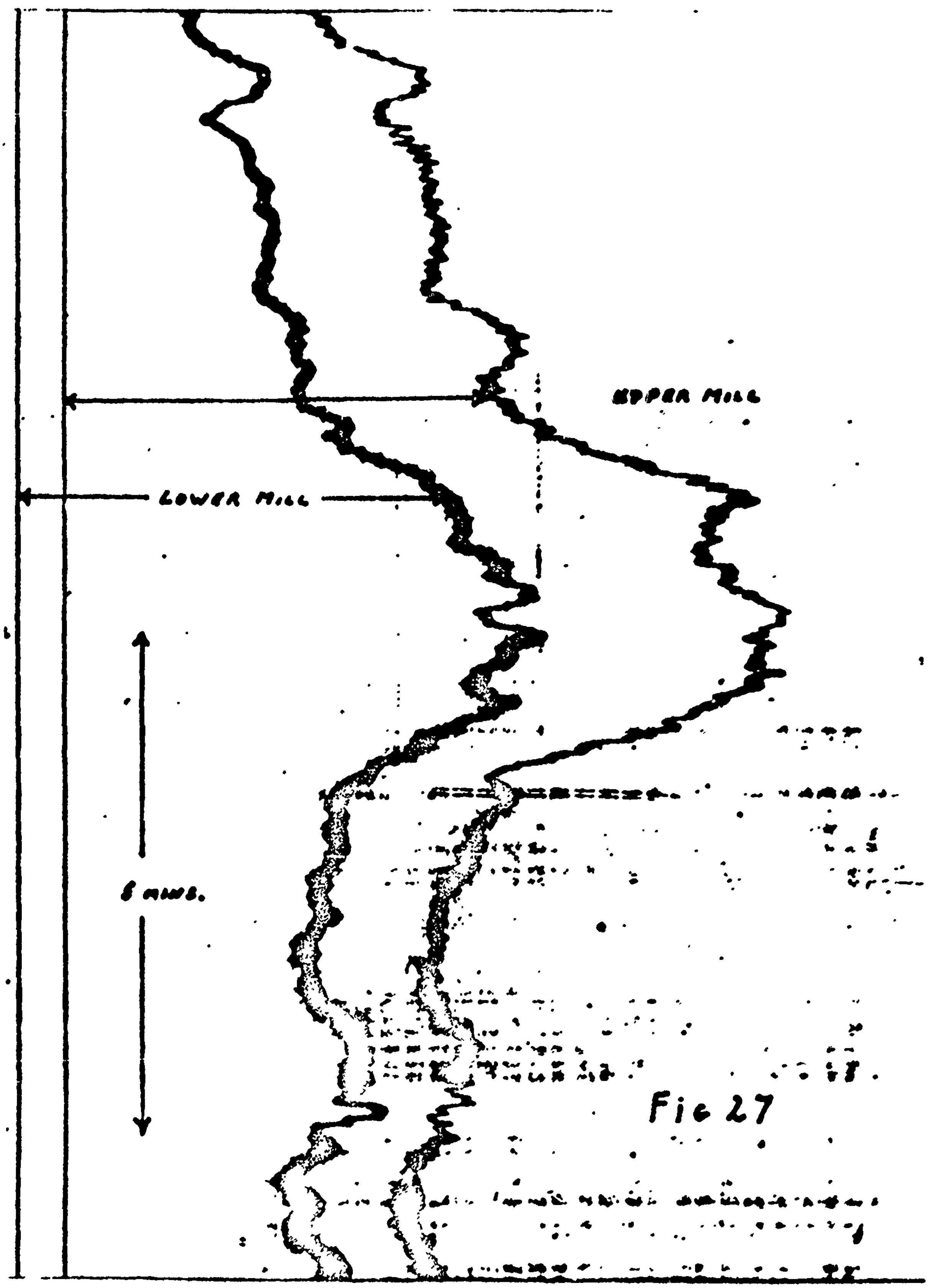


Fig 27

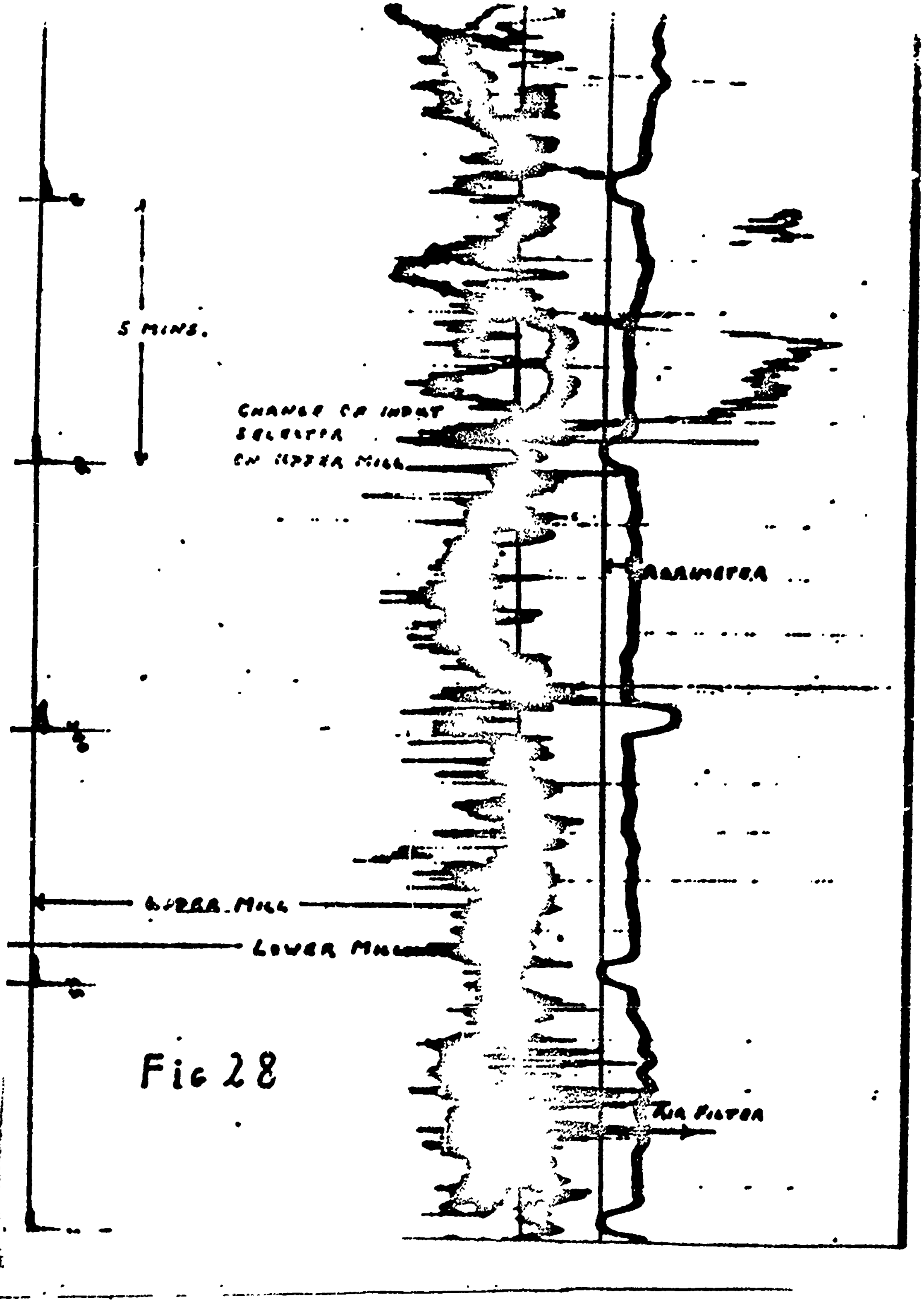
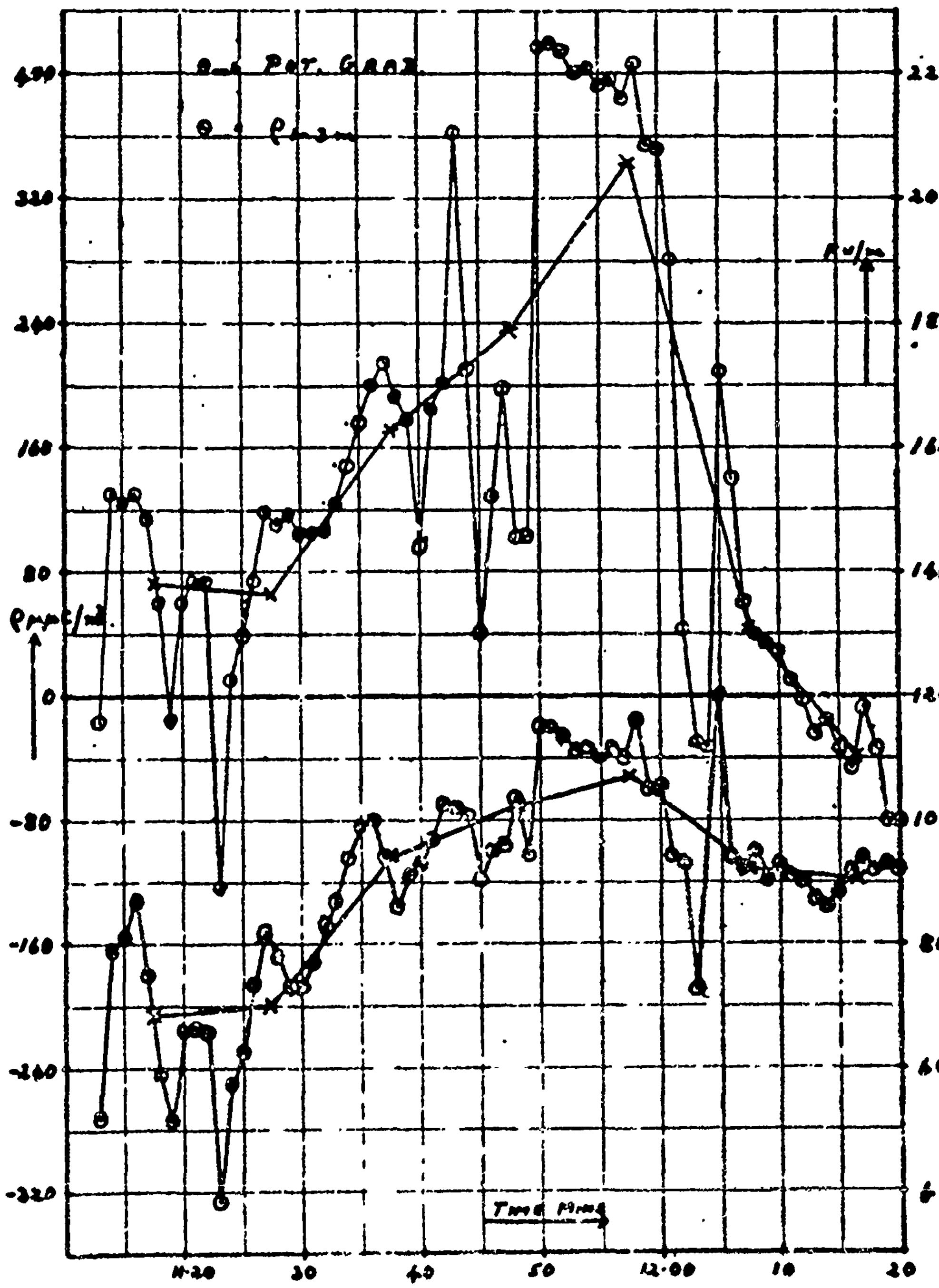
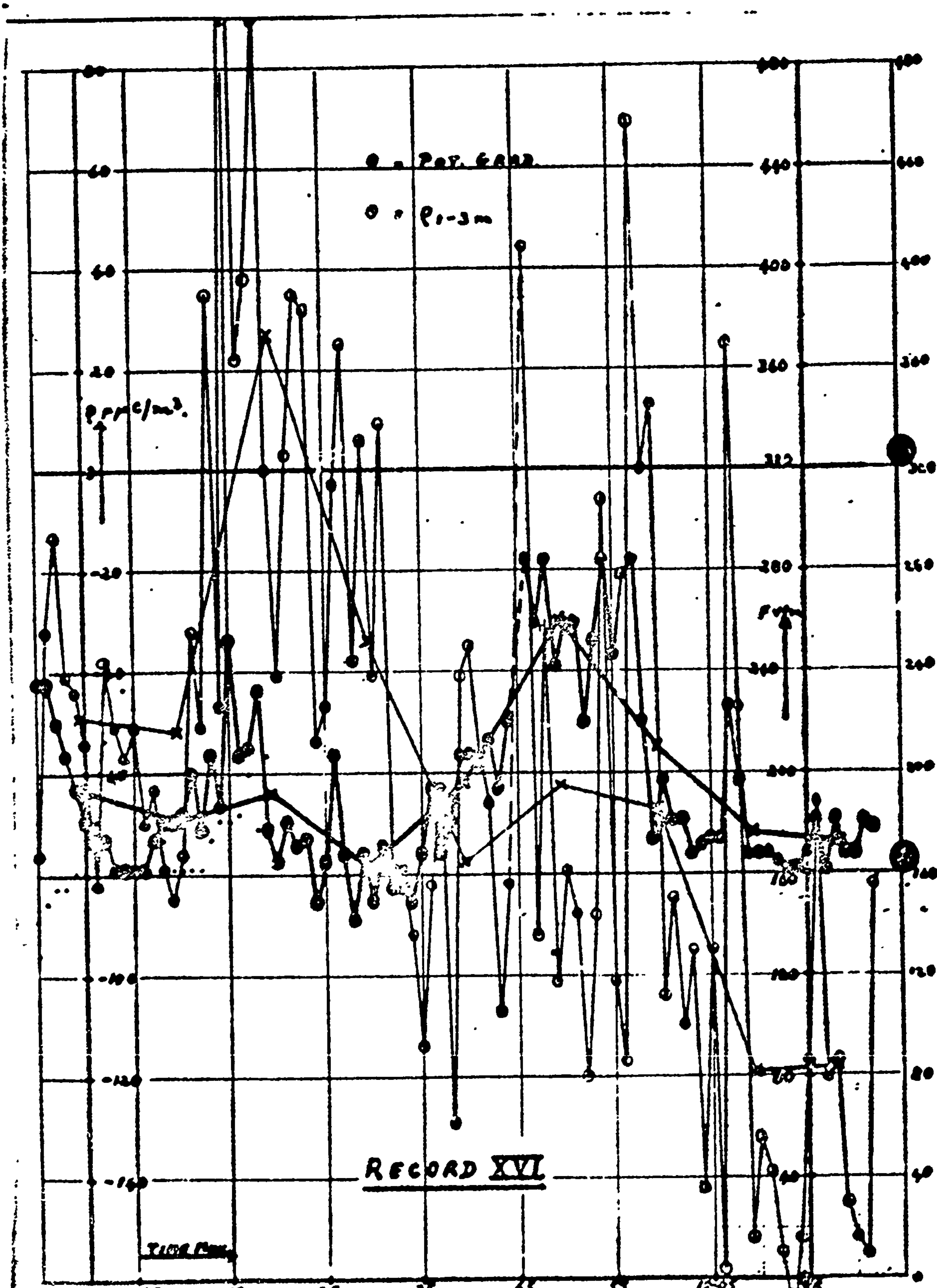

5 MINS.
CHANGE OF INPUT SELECTOR ON UPPER MILL
AMMETER
UPPER MILL
LOWER MILL
AIR FILTER

Fig 28



RECORD V


RECORD XVI

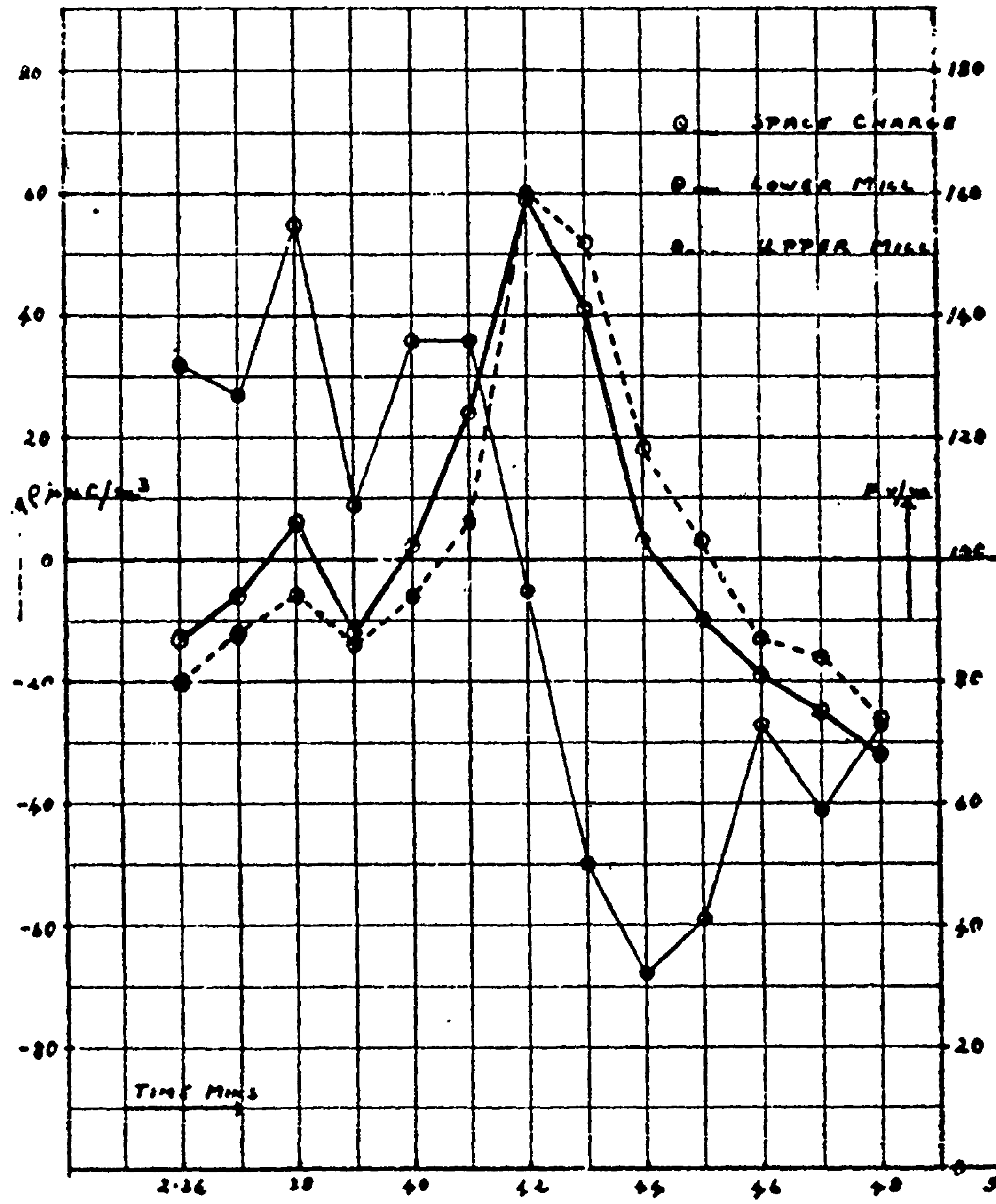

SPACE CHARGE
LOWER MILL
UPPER MILL
TIME MINS
2·36
38
40
42
44
46
48
50

FIG 30.

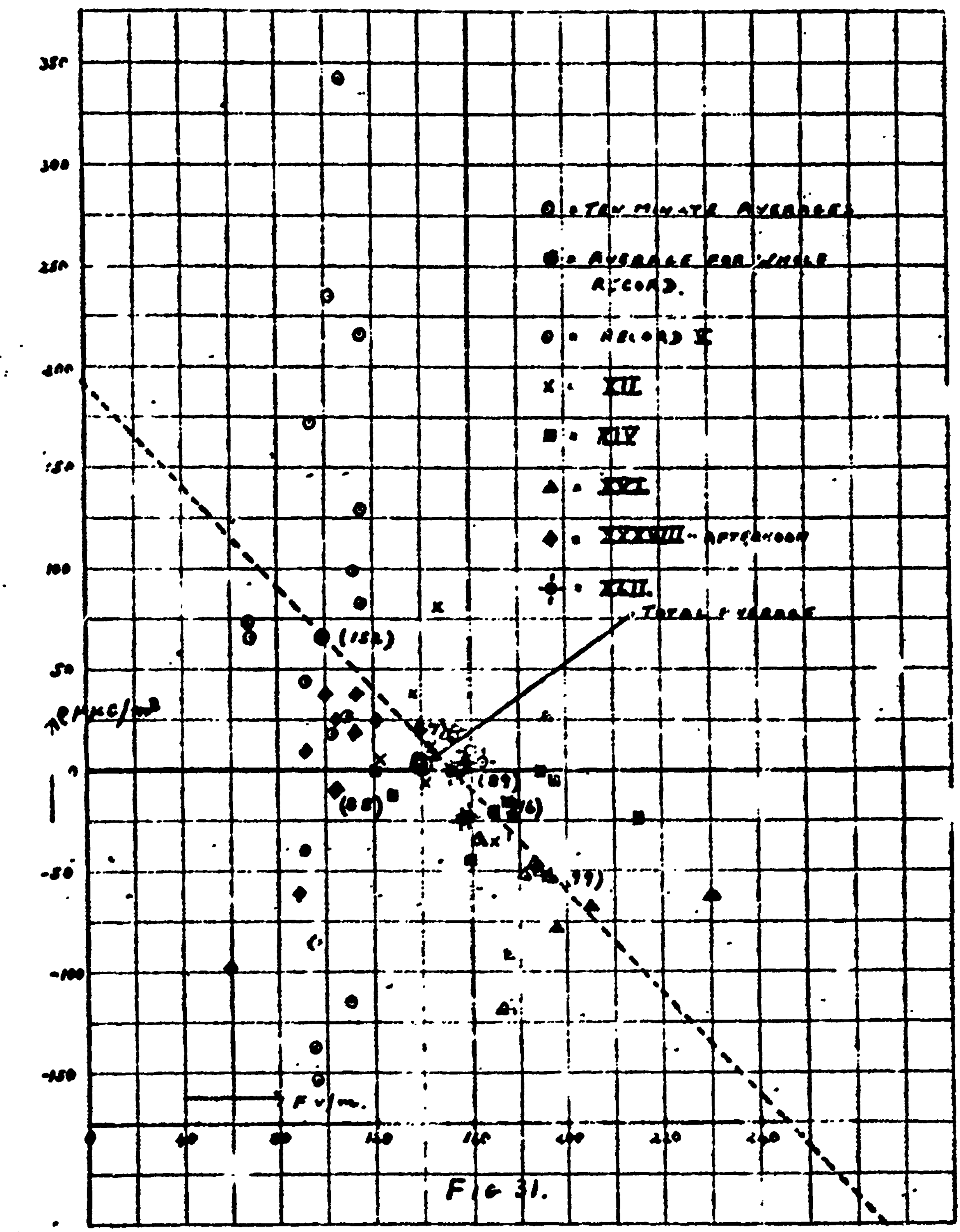
Such effects can be clearly seen by comparing Fig. 27 and Fig. 28, which are actual records of two potential gradient traces. Fig. 27 was taken in fine sunny conditions with clear sky and a light westerly wind of less than 1 m/sec. velocity. On the other hand, Fig. 28 was taken when a certain amount of cumulus cloud was present and the wind speed was about 5 m/sec. The difference in frequency and amplitude of the fluctuations is very apparent. Calculating the space charge variations corresponding to these fluctuations, results gave for Fig. 27 an average value of 10 $\mu\mu c/m^3$ and for Fig. 28 40 $\mu\mu c/m^3$. Such fluctuations may give rise to differences between the readings obtained from different apparatus a short distance apart, e.g. the instantaneous reading of the agrimeter might differ from that of the field mills by 6 v/m.

A total of six fair weather recordings was made, five with westerly winds and one with wind from the north. Record V shows part of the case of the northerly wind and Record XVI a typical example of westerly wind. Both records cover roughly the same time of day and in both cases the sky was cloudless. For Record V, the average value of the space charge was + 66·9 $\mu\mu c/m^3$ and for Record XVI - 58·7 $\mu\mu c/m^3$. The explanation of this phenomenon is that Durham City lies to the north of the site and the source of the positive charge is the smoke originating mainly from domestic fires.

8·3. Relation with Potential Gradient.

In the portion of Record XVI shown, and also less frequently in Record V, there are fluctuations in space charge with corresponding fluctuations in potential gradient over periods of one or two minutes. Over longer times, however, there is not a similar agreement; for example, Record XVI shows a general decrease in space charge while the potential gradient remains generally the same, and in some cases there is a "mirror image" effect between space charge and potential gradient for fluctuations over longer periods, of the order of 10 mins. Fig. 30 shows the analysis of the record reproduced in Fig. 27 and illustrates the "mirror image" effect.

The "mirror image" effect can be accounted for in terms of charges passing above the whole apparatus. If a positive charge passes above the apparatus, then it produces an increase in potential gradient at both mills, but this increase is greater at the upper mill than at the lower mill, so that there is an apparent negative space charge between the mills; if this had been a true negative space charge between the mills, then there would have been a decrease in the reading of the lower mill.



⊙ = TEN MINUTE AVERAGES
⬤ = AVERAGE FOR WHOLE RECORD.
⊙ = RECORD X
x = XII
■ = XIV
▲ = XVI
◆ = XXXVIII - AFTERNOON
✚ = XLII.
TOTAL AVERAGE
(152)
(85)
(89)
(77)
350
300
250
200
150
100
50
0
-50
-100
-150
F v/m.
40
80
120
160
200
240

Fig 31.

Using all the records in fair weather and plotting space charge and potential gradient for all 10-minute averages, and also averages for each record, Fig. 31 is obtained, showing a general tendency for a decrease in space charge with an increase in potential gradient. It is also to be noted that, except for Record V, the space charge is found to be negative and in the case of Record V the positive charge is ascribed to wind direction.

8.4. Effect of Reduction Factor.

The result, indicated by Fig. 31, of a negative space charge, increasing with increasing potential gradient, could be accounted for as a spurious effect if the two mills had different values of the "reduction factor". Such a difference might arise either from an error in the calibration of one or other mill, or from a true difference in exposure.

If, relative to the upper mill, the lower mill has a reduction factor R, then :

$$RF_L - F_u = \frac{\rho h}{\epsilon_0}$$

gives the true value of ρ, while :

$$F_L - F_u = \frac{\rho^1 h}{\epsilon_0}$$

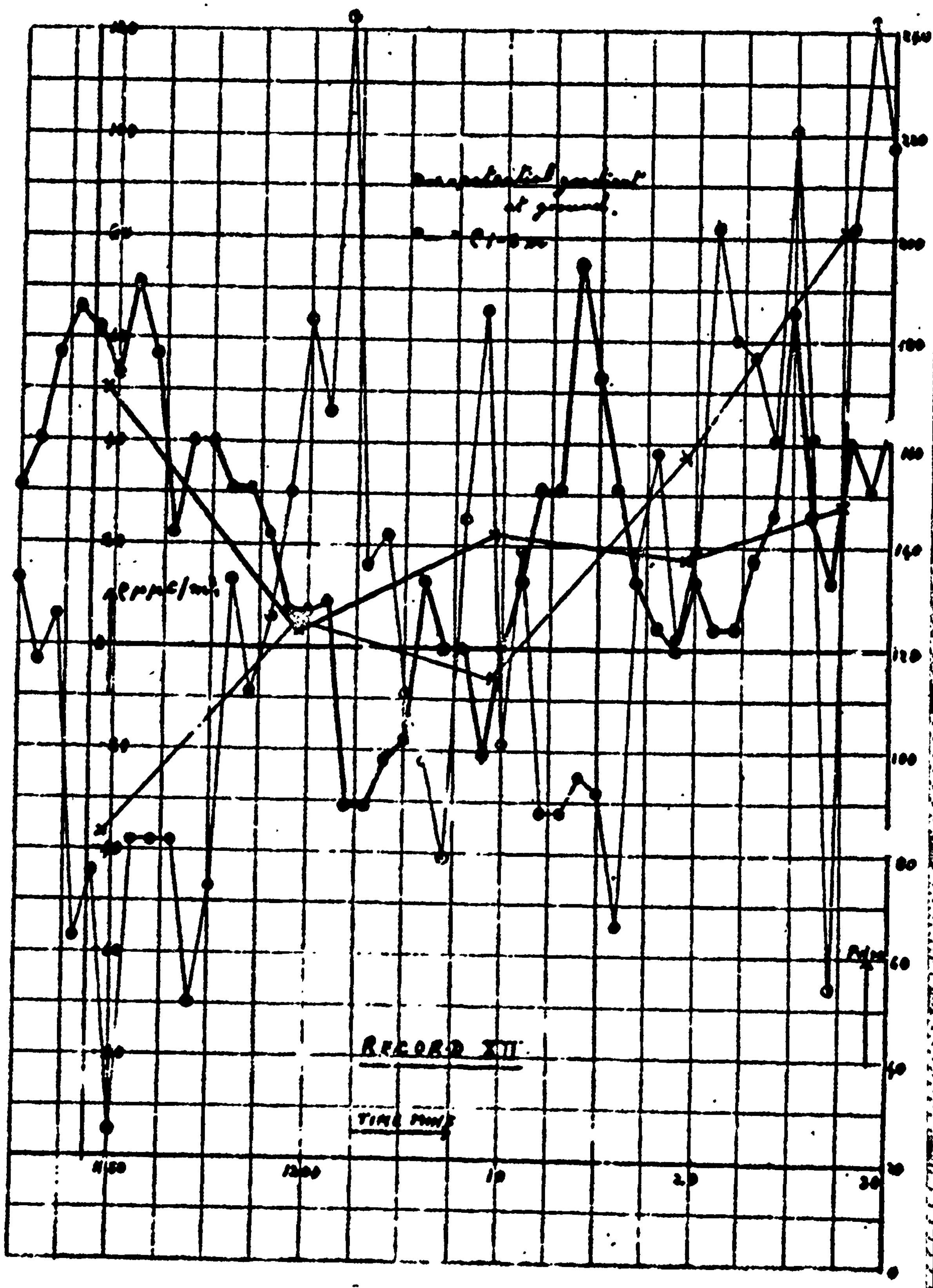
is the value ρ^1 indicated by neglecting R.

Thus :

$$\rho^1 = \frac{\epsilon_0}{h}(R-1)F_L + \rho$$

gives a straight line relating ρ^1 and F_L with a negative slope.

Using the values from Fig. 31, to account for the line, R = 1.24 would be required and the true value of ρ would be 190 $\mu\mu c/m^3$. This would make the true difference between F_L and F_u 43 v/m, which is certainly incorrect. Also it is quite impossible that R should be so great as 1.2. It can be concluded that the relation between ρ and F is not to be accounted for in terms of a reduction factor.

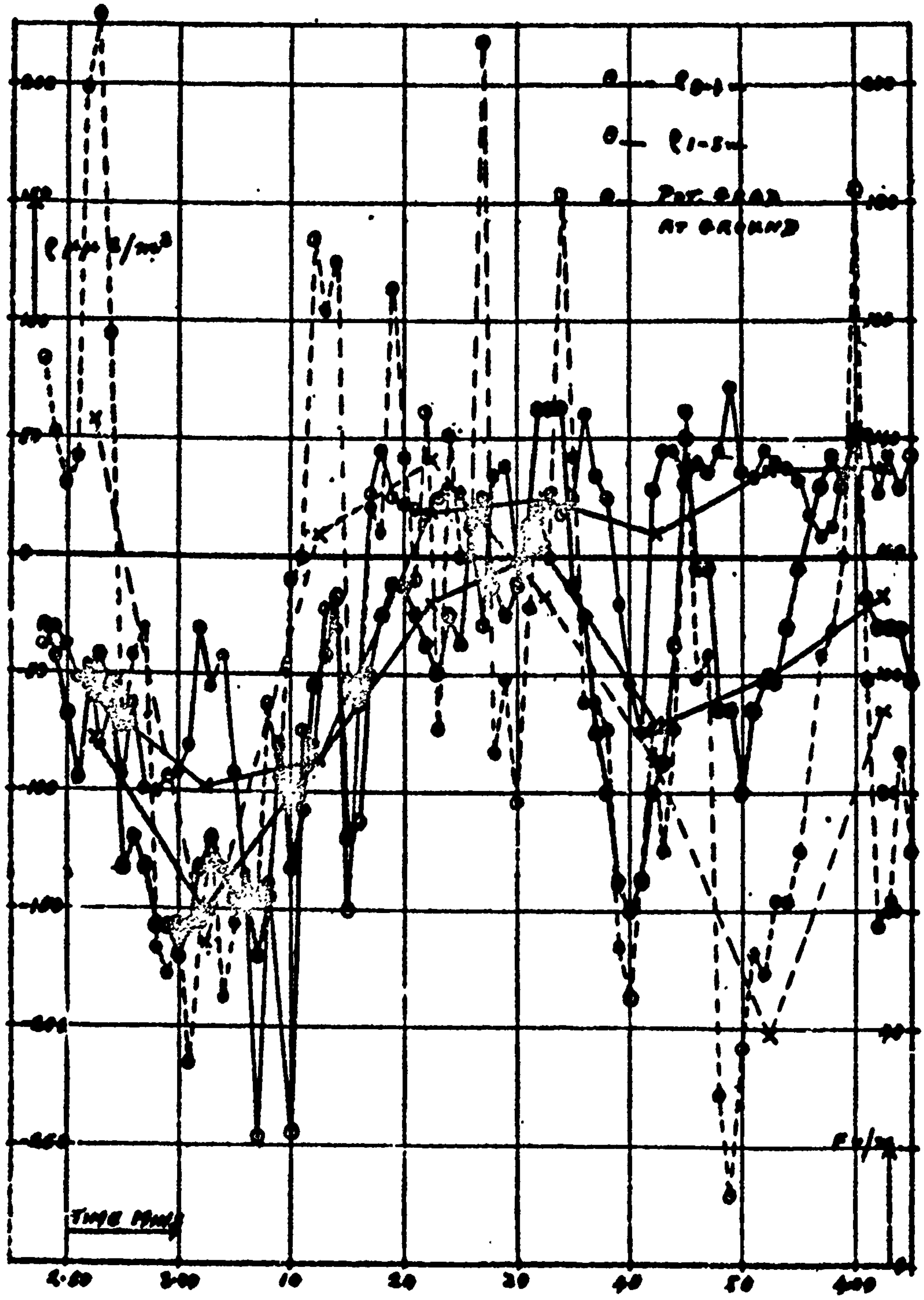

RECORD XII
TIME MINS
11.50
12.00
10
20
30
240
220
200
180
160
140
120
100
80
60
40
20
0

8.5. Effect of Radioactivity.

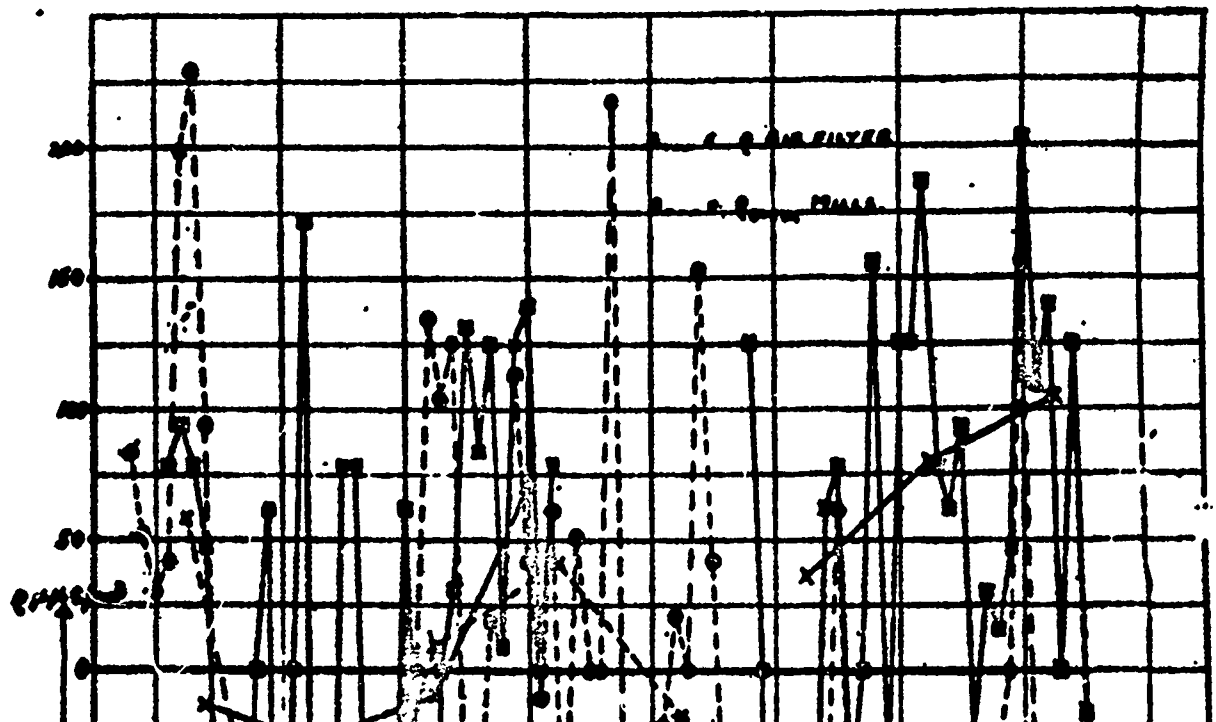
If the negative space charge between 1 and 3 metres is a real space charge, not a spurious effect, and if it can be considered as secondary space charge, in the terms of the definition of para. 2·1, then we can see from the results of para. 2·2 that it can be ascribed to the conductivity being greater at 1 m than at 3 m. It therefore remains to consider how such a difference in conductivity might arise.

It has already been pointed out (para. 2·5) that the absence of the electrode effect may be associated with the effects of radioactive substances in the earth's crust. α and β rays from these substances produce ionization close to the earth's surface and so give an increased conductivity, which is not confined to the region in which the ions are produced but which extends upwards; since the negative ions, which move upwards in the normal positive potential gradient, can appreciably affect the conductivity only as long as they remain small ions, it follows that the enhanced conductivity must fall off with increasing height since the number of ions which remain small ions is less the farther they have to travel. Thus the effect of radioactivity is to give a contribution to the conductivity which decreases from 1 m to 3 m. Under normal conditions, the mean life of a small ion in the lower atmosphere is about 40 seconds; thus, if the potential gradient is 100 v/m, a small ion of mobility about 1·5 c.g.s. units will, on the average travel 60 cm. Thus a fraction of the ions will reach 85 cm [the true level of the nominal "1 metre"] but very few reach 285 cm. Further, it is clear that the greater is the potential gradient the greater is the average travel of the ions and thus the larger the fraction that reach 85 cm. We thus see that the effect of radioactivity can account quite simply for the relation between space charge in the region 1-3 m and potential gradient, as shown by Fig. 31. The result, from Fig. 31, that for zero potential gradient there would be a positive space charge, suggests that when ionization due to radioactivity does not reach the levels concerned, there is a "natural" positive space charge.

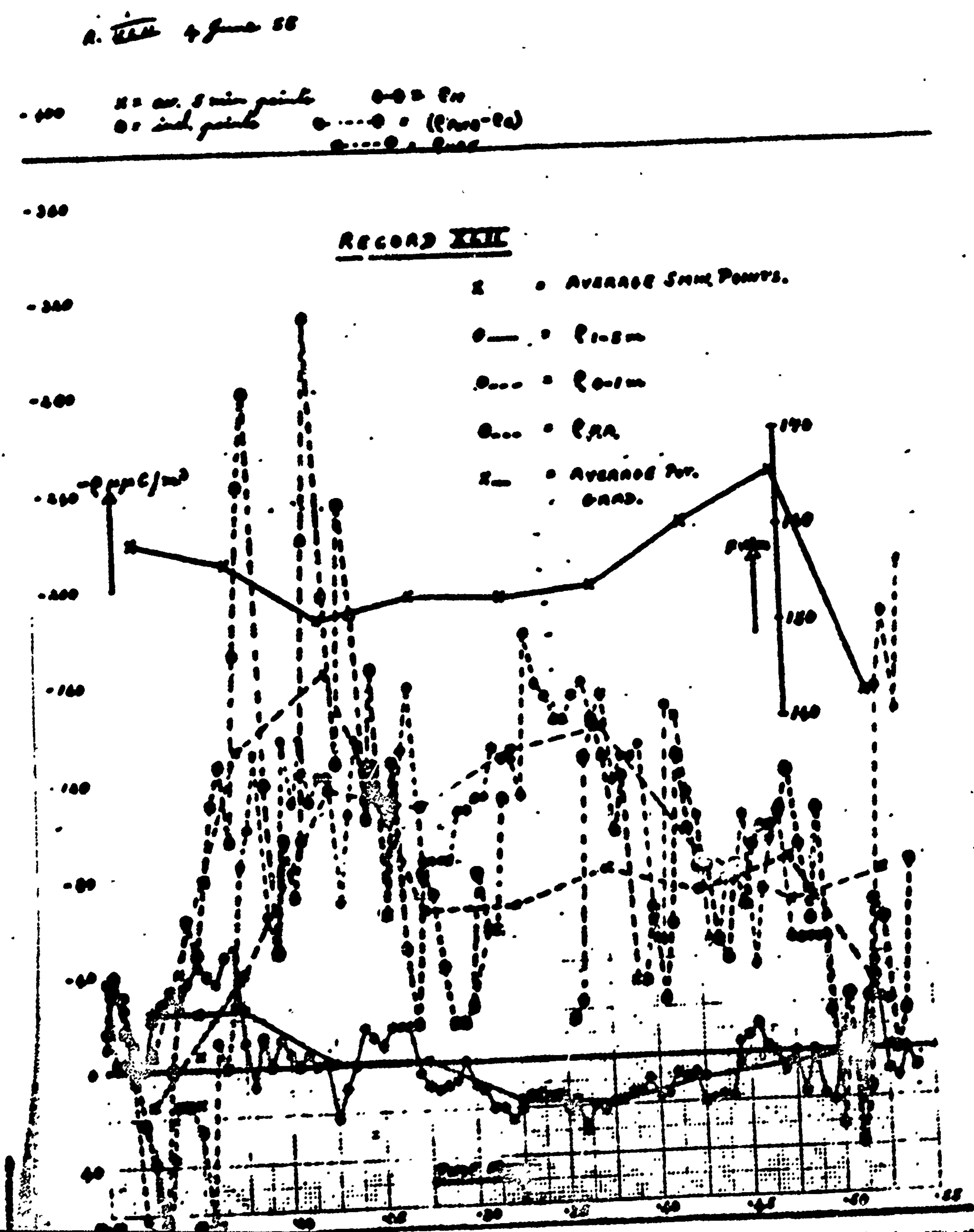
The effect described and explained above is also shown in more detail in Fig. 30, where the time lags of 2 minutes between potential gradient maxima and space charge maxima are in agreement with what might be expected from the effect of radioactivity. Record XII also shows the same effect over the earlier part of the record. Record XXXVIII shows negative space charge for lower potential gradients than would be expected from Fig. 31; this may be accounted for by the fact that heavy rain, which fell prior to this recording, will have "washed out" large ions and nuclei and will therefore have increased the average life of small ions.



RECORD XXXVIII - AFTERNOON A.



RECORD XXXVIII - AFTERNOON B.



RECORD XXII
AVERAGE 5 MIN POINTS.

The argument above, that the greater the potential gradient, the greater the negative space charge observed from 1 to 3 metres, can be extended to suggest that, at the same time there will be a smaller negative space charge from 0 to 1 metres. In the Record XXXVIII (afternoon A), there is included the space charge below the lower mill obtained by comparison of the potential gradients measured by the lower mill and by the agrimeter. The expected parallelism between the traces is, in general, to be noticed.

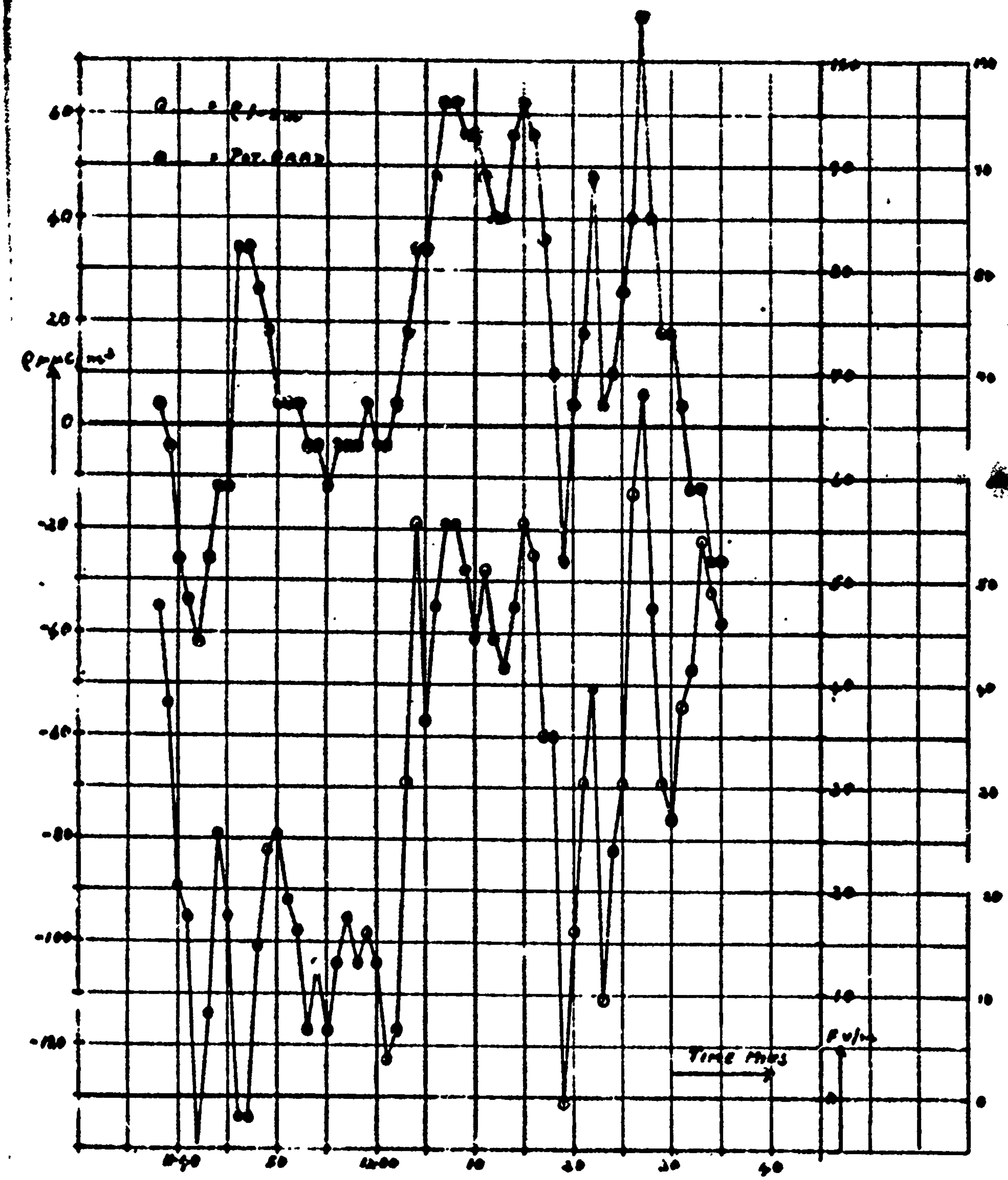
8.6. Comparison with Filtration Results.

The air intake of the filtration apparatus is at 65 cm. height, so, for a fair comparison it would be necessary to find the space charge at this level from the field mills. If it can be assumed that the potential gradient changes fairly uniformly from the ground up to the level of the lower mill at 85 cm, then measurement of the potential of the lower mill gives a value of the potential gradient at 42·5 cm; measurement of the potential gradient at the lower mill is that at 85 cm, and so the space charge from these two results is that centred about 63·75 cm. Therefore a comparison of the results of the filtration apparatus can be compared fairly with the value of space charge deduced from the potential and potential gradient at the first mill. If, however, the negative space charge decreases with height, as would be expected from the effect of radioactivity, then the results from the mills should give a greater negative space charge than from the filtration apparatus.

Record XLII shows results in good agreement with expectation except between 12·13 and 12·36 where the filtration apparatus shows large fluctuations. However for the Record XXXVIII (afternoon B) the agreement is far less good, giving averages of + 84·1 $\mu\mu c/m^3$ from the filtration apparatus and − 54·9 $\mu\mu c/m^3$ from the measurements with the mill.

One of the disadvantages of the filtration method is the possibility of selective filtering by reason of bound charges on the exposed case of the filter. In a positive potential gradient, the negative bound charge on the case might repel negative ions that would otherwise enter the filter and attract extra positive ions, and hence produce an apparent positive space charge. This effect would be much more evident with small ions than with large ions and might only become serious when conditions are such that small ions are exceptionally predominant, such as we have already suggested to occur for Record XXXVIII when large ions and nuclei have been washed out.

The agreement between the field mill and filtration results in cases such as Record XLII suffices to show that the field mills do, in fact, give the space charge and that there is no serious error in the assumption that the lines of force are vertical at the mills.



RECORD XXII

CHAPTER IX. RESULTS IN DISTURBED WEATHER.

9·1. General Results in Rain.

Results have been obtained under various conditions of rain; the first important conclusion is that abnormally large values of the space charge between 1 and 5 m [i.e. values much larger than in fine weather] do not occur for light or medium rain. It appears to require a rate of rainfall of over 0·1 mm/min to produce such effects, presumably by splashing at the earth's surface; it may well be that the critical rate of rainfall depends on the state of the ground. An example of results in moderate rain [no rate of rainfall available] is shown in Record XXII. If, however, measurements are made of the space charge below 1 m, then large values are found with rates of rainfall over about 0·06 mm/min, a value again perhaps depending on the state of the ground. The result that the production of space charge by splashing depends on the rate of rainfall is in agreement with results of Adkins (1958).

Smith (1955) put forward the idea that the negative potential gradient usually found during continuous rain might arise from negative charges produced by splashing and subsequently diffusing upwards. The present results show that this theory is not tenable for light or moderate rain.

The earlier part of Record XXVIII - morning A, in which the rate of rainfall never exceeded ·02 mm/min, gave the following average results from 10·20 to 10·50:

$$\rho_{FA} = -170\ \mu\mu c/m^3$$

$$\rho_{0-1} = -109\ \mu\mu c/m^3$$

$$Fg = -182\ v/m$$

$$i = +5{\cdot}67\ \mu\mu a/m^3$$

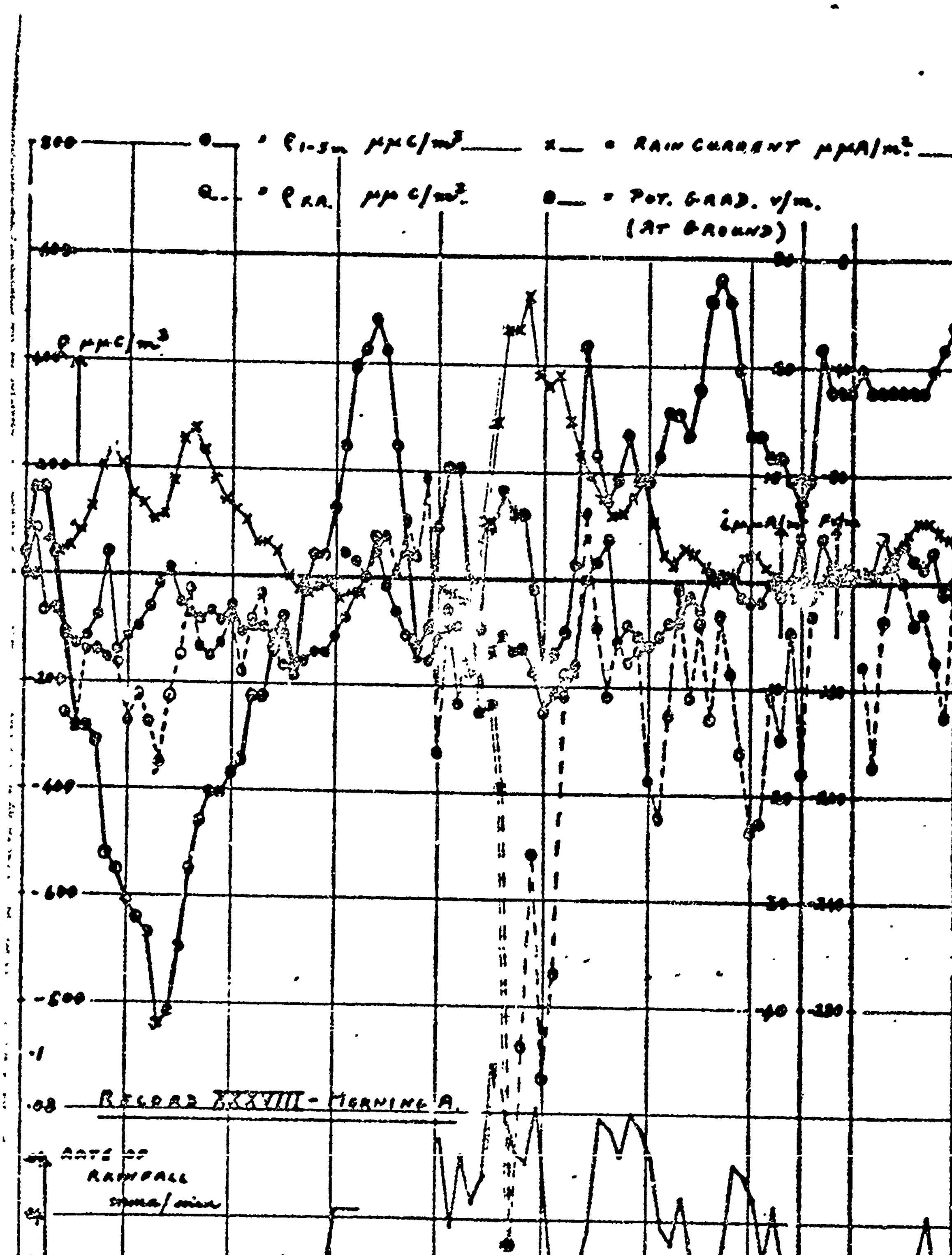
$$r = 0{\cdot}006\ mm/min.$$

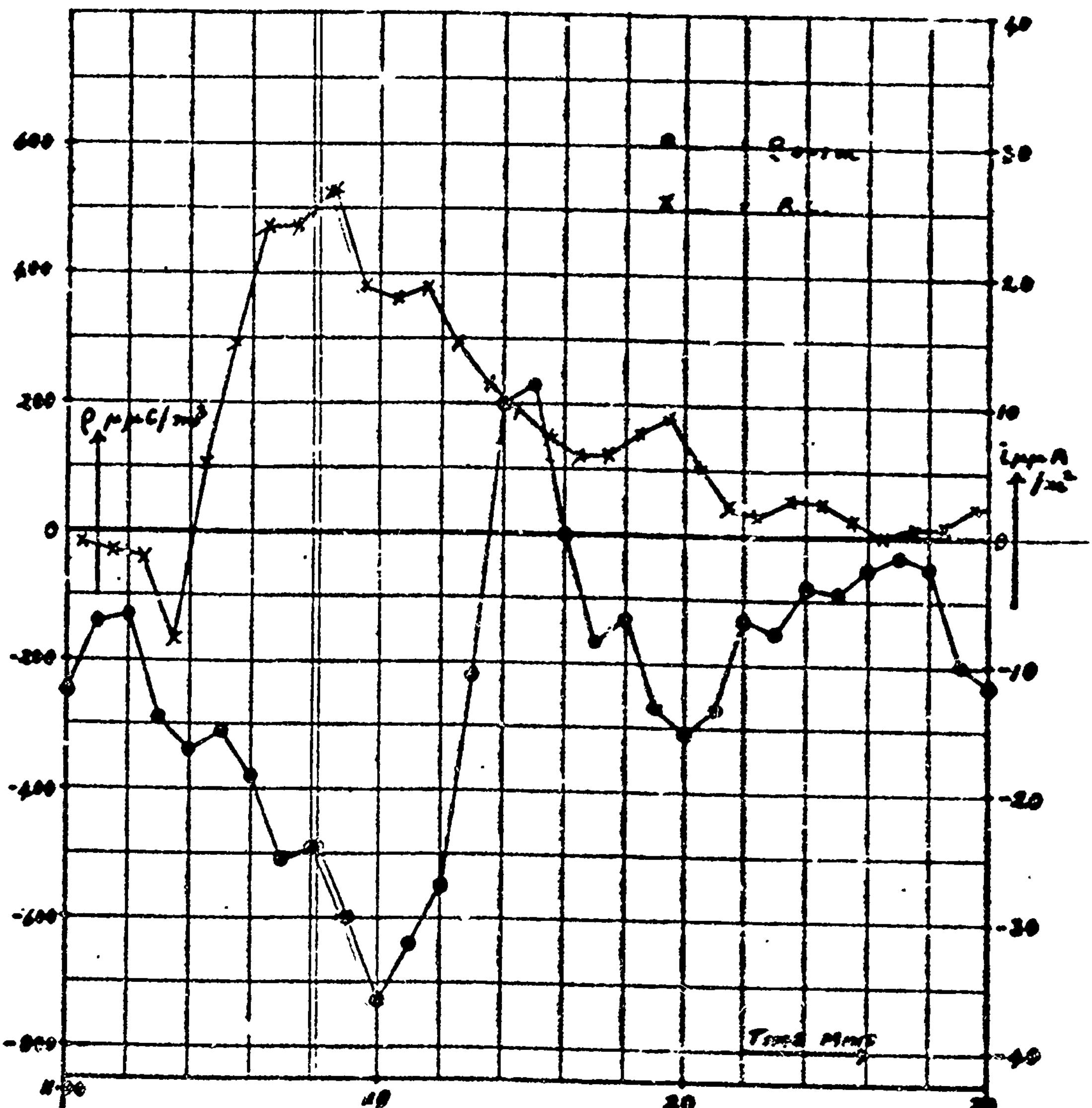
Here the discrepancy between ρ_{FA} and ρ_{0-1} gives a greater negative value for ρ_{FA}, but, since the potential gradient was negative, the same explanation as in para. 8·6 may hold, with reversed signs.

The space charge of the actual rain can be estimated if an average drop speed can be assumed; if this is 3 cm/sec, then $\rho_R = +1{\cdot}89\ \mu\mu c/m^3$, which is very small compared with ρ_{FA}. For greater precision, a result of Best (1950) can be used:

$$W = CI^r$$

where W is the liquid water in mm^3/m^3, I is the rate of rainfall


ρ 1-5m μμC/m³
x = RAIN CURRENT μμA/m²
ρ R.A. μμC/m³
POT. GRAD. v/m. (AT GROUND)
ρ μμC/m³
RECORD XXXVIII - MORNING A.
RATE OF RAINFALL mms/min
TIME Hrs.



RECORD XXXVIII - MORNING B.

in mm/hr and C is a constant equal to 67; $r = 0{\cdot}846$.
From this one can obtain:

$$\rho = \frac{0{\cdot}24\ 1}{I^{0{\cdot}154}}$$

where i is the rain current.

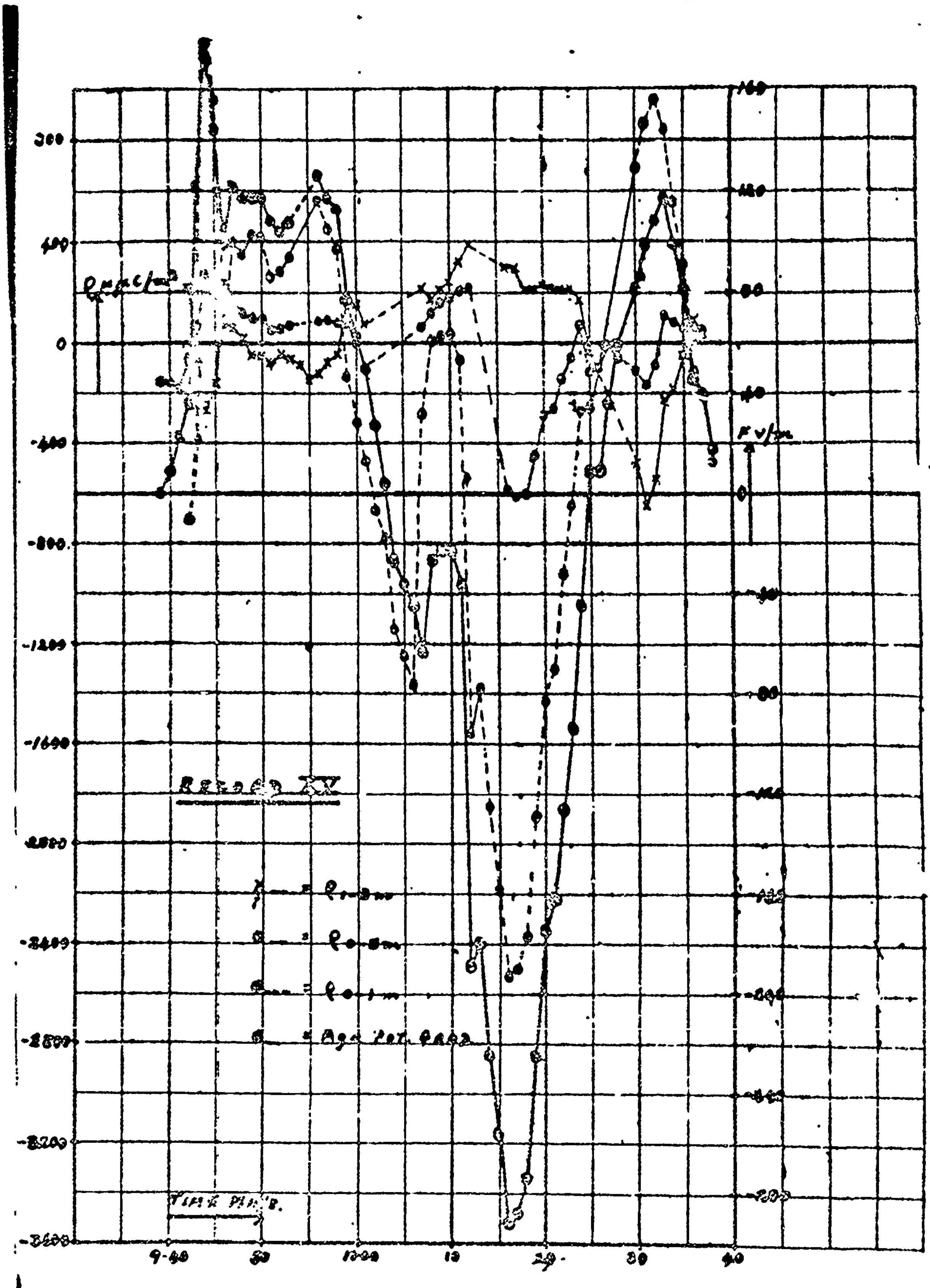
With the figures above, $\rho_R = +1{\cdot}6\ \mu\mu c/m^3$.

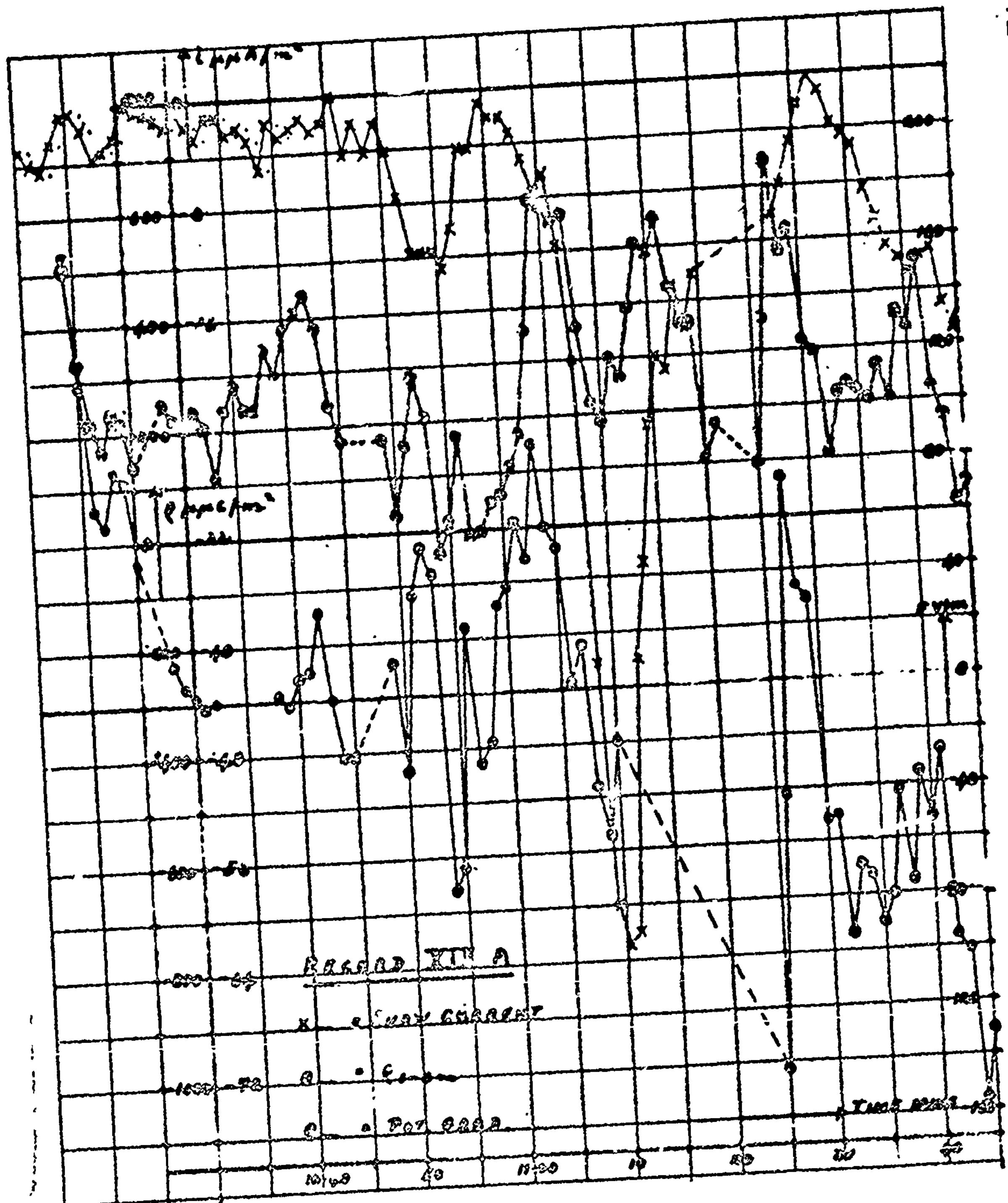
9·2. Results in Heavy Rain.

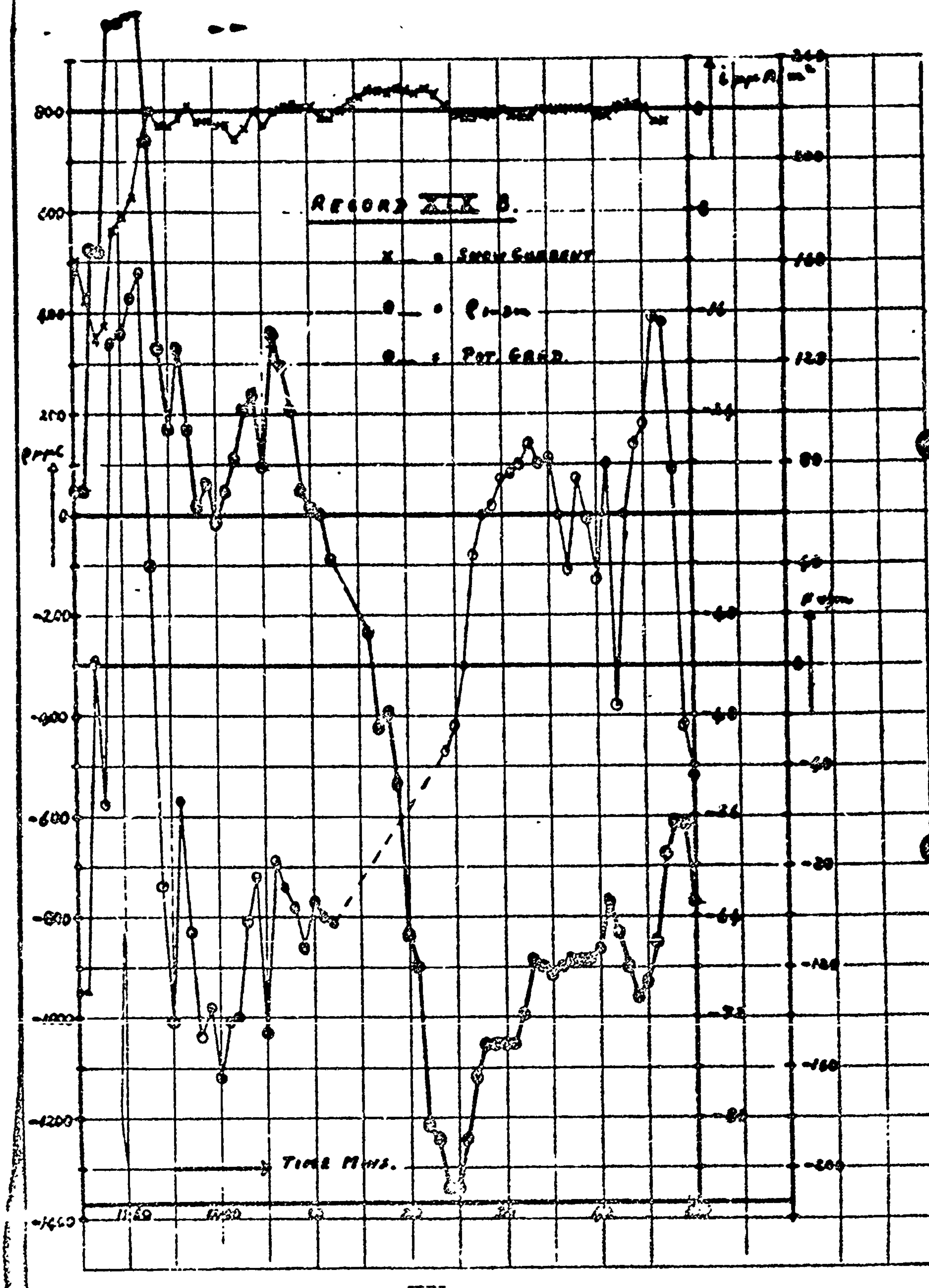
Record XXXVIII - morning (on two diagrams to avoid confusion) shows a period during which there was heavy rain. In addition to results with the field mills, observations at the same time are also available of rain current and rate of rainfall.

Although, between 11·05 and 11·10, rate of rainfall, rain current and space charges reached their maximum values, the potential gradient remained fairly small. At 1 to 5 metres, the space charge never exceeded values that exist in fair weather conditions, but below 1 metre both the filtration apparatus and the results from the field mill showed large values.

In order to explain these results, it can be assumed that the rain, on reaching the ground, produces negative ions by splashing. Whereas some of these negative ions are drawn into the ground by the negative potential gradient, there are some which diffuse upwards to heights of less than 1 m. The rain current is then positive by reason of the splashing process, and one cannot be certain what charge was originally on the rain; even if the whole rain current of about 20 $\mu\mu c/m^2$ were on the falling rain, this, falling at a few metres/sec. would only give a space charge of 10 $\mu\mu c/m^2$ or less, quite inappreciable compared with the space charge of the ions. Since the potential gradient is negative, the filtration apparatus carries a positive surface charge and so may selectively attract towards itself negative ions, giving an explanation of the larger values obtained by the filtration apparatus. The production of a negative space charge with the potential gradient negative is in contradiction to the results of Adkins (1958) who found the charge to be opposite in sign to the potential gradient; on the other hand, the production of negative space charge is in agreement with the early results of Lenard (1892).


RECORD XV
TIME MIN'S.
9-40
50
10-00
10
20
30
40
F v/m
0





RECORD XIX B.
x — Snow Current
TIME MINS.

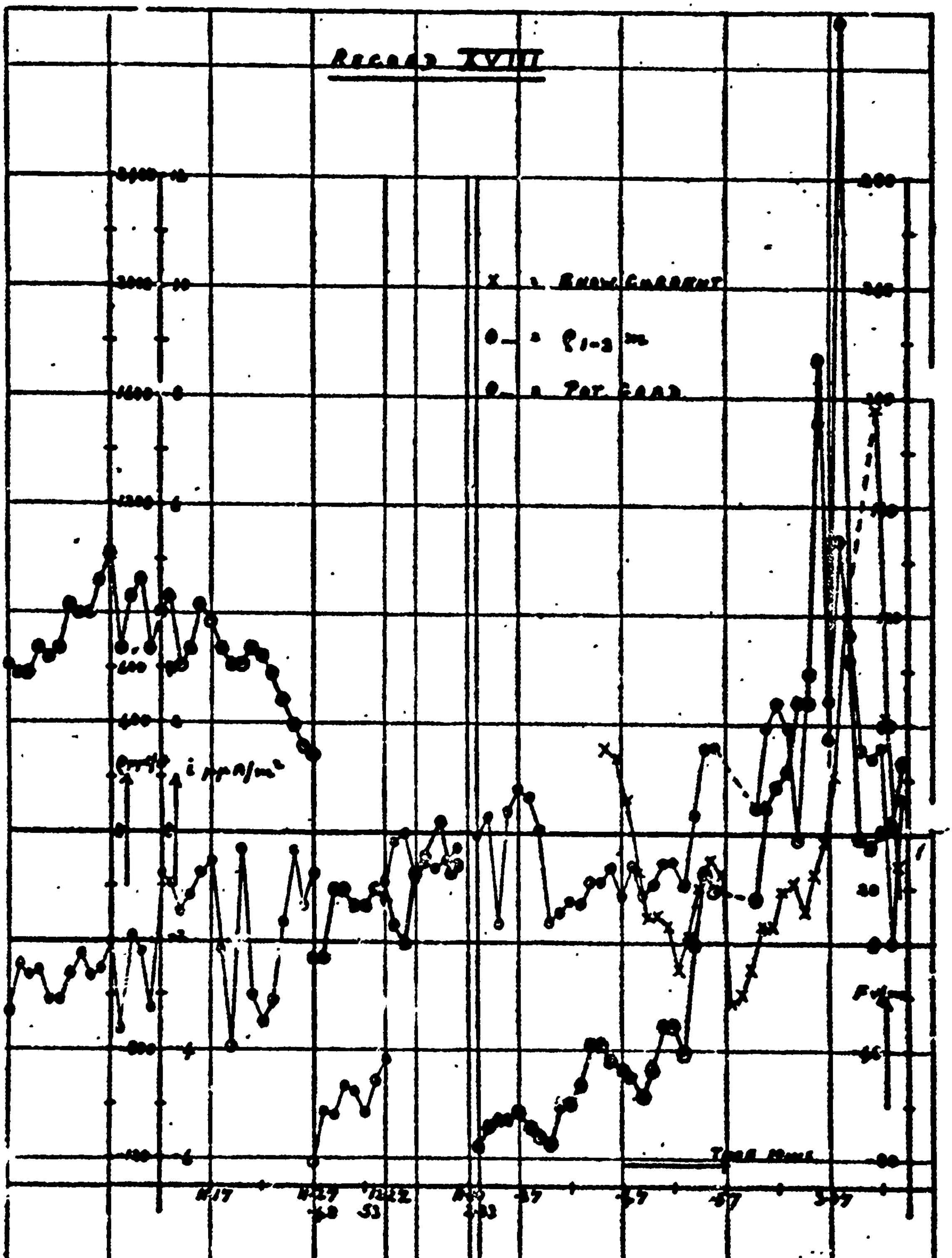
Record XV is that of a shower, with heavy rain; unfortunately, neither the rain current nor the rate of rainfall was being measured, but it was estimated that the rate of rainfall was from 0·2 to 0·3 mm/min., at its heaviest, around 10·10. The maximum negative values of space charge and potential gradient did not appear until several minutes after the greatest rate of rainfall, and, again, both were negative. Since the potential gradient at 1 m. remained in the region of - 30 v/m, the change in potential gradient at the ground is due entirely to the space charge below 1 m. An interesting feature of this record is that after 10·20, when the rain had completely ceased, the potential gradient at the ground became positive, but a negative space charge now appeared at 1 - 3 m; this, presumably, was some of the charge previously below 1m and now moving upwards by diffusion and in the field.

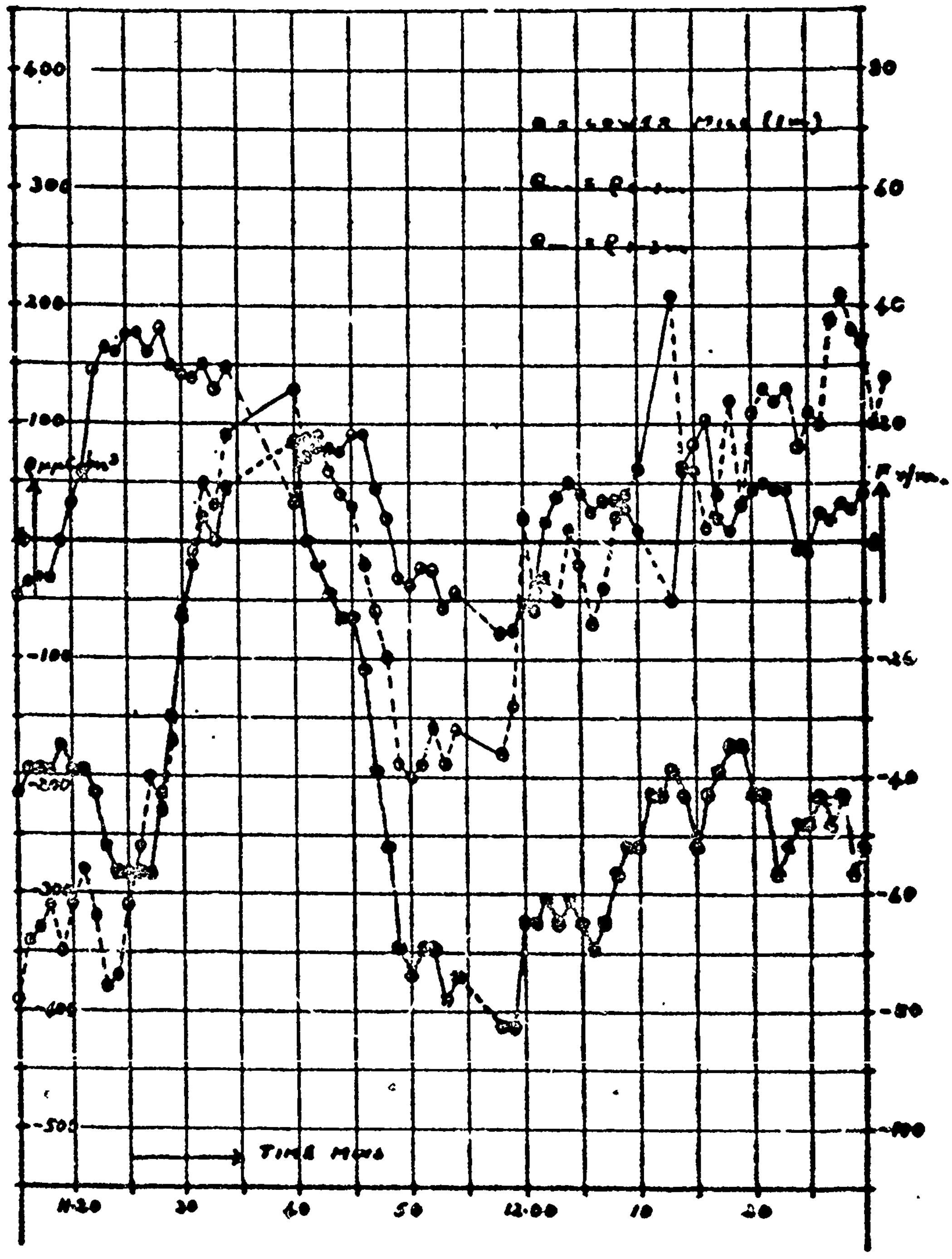
9·3. Results in Snow.

Record XIX A and B is typical of results in snow, with heavy snowfall up to 12·00 and ceasing completely by 12·10. The heaviest snowfall occurred at times corresponding to peaks in the records, at 10·55, 11·10, 11·24 and 11·44; unfortunately some of these coincided with accidental breaks in some of the records [repair of mill driving belt, reloading of camera].

The negative space charge found is comparable with that in heavy rain; however, since the snow carries a negative charge and falls slowly, it may well be that some of the space charge is that on the snow itself. If it is assumed that the snow falls at a rate of 0·2 m/sec, then, at about 11·10, when the snow current was about - 60 $\mu\mu c/m^2$, the space charge on the snow would only be - 300 $\mu\mu c/m^3$, while the total space charge amounts to - 400 $\mu\mu c/m^3$; at other times, the discrepancy is greater, showing that often there must be negative space charge other than on the precipitation; this is especially true at the end of the snowfall at 12·00 hours.

The results might be explained if the snow contains small, negatively charged, particles which fall very slowly and so give an appreciable space charge. This would agree with the persistence of negative space charge after the end of the snowfall, but not so well with the coincidence in time of the maxima of snow current and space charge at 11·10 and 11·45. The rise of space charge to positive values after the snow current maxima might be accounted for by positive charges liberated by the impact of the snow on the ground and diffusing upwards.


RECORD XVIII
X — = SNOW CURRENT
Time Mins



400
300
200
100
-100
-200
-300
-400
-500
80
60
40
20
-20
-40
-60
-80
-100
TIME MINS
11.20
30
40
50
12.00
10
20

RECORD XIII

Record XVIII gives another example of snow results; the morning portion of the record (broken in two places by the need for belt repairs) is of the same type as the previous record. But in the afternoon, conditions are different; at first, there is a positive snow current and a negative potential gradient with negative space charge at 1 - 3 m; later, for a while, we have the normal snow conditions of negative current and positive potential gradient, but a positive space charge; in the last period, all three quantities are positive. It is difficult to give a satisfactory explanation of the phenomena.

9·4. Results in Mist.

No fog or very thick mist occurred in Durham during the period when the apparatus was in operation, bur Record XIII shows results obtained during a wet mist with visibility about 20 yards. The general result in the later part of the record, showing positive space charge and negative potential gradient; this may be the same effect as that found in fair weather and ascribed to radioactivity [see para. 8·5], but with reversed sign. The conductivity in mist is lower than in clear air, because the small ions attach themselves readily to the water droplets, hence the time lags between changes in potential gradient and changes in space charge are longer, and this is enhanced by the low potential gradient.

CHAPTER X. CONCLUSION

10·1. Results Achieved.

The most important result achieved is that it has been found possible to use a double field mill as a collector, which attains the potential of its surroundings, as does any ordinary collector. The double field mill does more than this, it not only gives a record of the potential at its position, it also gives recordings for the potential gradient. As compared with, for example, a radioactive collector, the double field mill does not disturb the electrical conditions in its neighbourhood.

The use of two double field mills to give the space charge in a region is an advance on other potential gradient methods, since there is no disturbance of natural electrical conditions. The method of measuring space charge from potential gradients cannot be as sensitive as other methods, since it depends upon the rather small difference of two potential gradients, but, as the present work has shown, there seem to be inaccuracies in apparatus, such as the filtration apparatus used, when small ions are present in quantity.

The actual records discussed must be considered to be just a preliminary sample of what could be obtained if the apparatus were put into use, with some of the improvements to be suggested, for a period of years. With an extensive series of results, it might be possible to confirm or disprove some of the explanations suggested here.

10·2. Improvements to Apparatus.

Some improvement in the driving belts is necessary; the plastic belts snapped, on an average, every two hours. A leather belt might be an improvement, but might stretch and might be too highly conducting in wet weather.

A pulley arrangement for more rapid alteration of heights would be an advantage.

The manual reversal of the mill potential whenever the potential gradient changes sign is unsatisfactory, and it should not be too difficult to arrange an automatic device which would reverse the slide voltage when the slide was driven to zero and remained there for, say, 30 seconds.

10.3. Future Developments.

In addition to the continuation of recordings on the same basis as reported here, the use of a double field mill to bring apparatus to the potential of its surroundings can have other applications in atmospheric electricity.

One of the interesting possibilities is that of the measurement of both polar components of the air-earth current at levels above the ground. If two horizontal plates are set up, separated by a thin sheet of insulating material, and put, by a double field mill at the potential of their surroundings, then each plate will receive one polar component of the air-earth current, and this can be measured. The effects of potential gradient changes could be eliminated or corrected for.

Another possibility would be to use the double field mill to bring to the potential of its surroundings such conductors as the outer casing of the filtration apparatus described in Chapter VII, and thus remove the surface charges which give rise to the selective filtering discussed in para. 8.6.

REFERENCES

Adkins, C.J. 1958. "Some measurements in atmospheric electricity." Ph.D. Thesis [Cambridge University].

Behacker, M. 1910. "Zur Berechnung des Erdfeldes unter der Voraussetzung homogener Ionisierung der Atmosphäre." S.B. Akad. Wiss, Wien. 119. pp. 675-684.

Benndorf, H. 1906. "Über gewisse Störungen des Erdfeldes mit Rucksicht auf die Praxis luftelektrischer Messungen." S.B. Akad. Wiss, Wien. 115. pp. 425-456.

Best, A.C. 1950. "The size distribution of raindrops." Quart. J.R. Met. Soc. 76. pp. 16-36.

Brown, J.G. 1930. "The relation of space charge and potential gradient to the diurnal system of convection in the lower atmosphere." Terr. Magn. Atmos. Elect. 35. pp. 1-15.

Chalmers, J.A. 1946. "The ionisation in the lowest regions of the atmosphere." Quart. J.R. Met. Soc. 72. pp. 199-205.

Chalmers, J.A. 1953. "The agrimeter for continuous recording of the atmospheric electric field." J. Atmosph. Terr. Phys. 2. pp. 311-321.

Chauveau, B. 1902. "Recherches sur l'électricité atmosphérique." Mem. II p.103.

Daunderer, A. 1907. "Luftelektrische Messungen." Phys. Z. 8. pp. 281-286.

Daunderer, A. 1909. "Über die in den unteren Schichten der Atmosphäre vorhandenen freie elektrische Raumladung." Phys. Z. 10. pp. 113-118.

Ebert, H. 1901. "Aspirationsapparat zur Bestimmung des Ionengehaltes des Atmosphäre." Phys. Z. 2. pp. 662-666.

Gish, O.H. and Wait, G.R. 1950. "Thunderstorms and the earth's general electrification." J. Geophys. Res. 55. pp. 473-484

Gunn, R. 1948. "Electric field intensity inside of natural clouds." J. Appl. Phys. 19. pp. 481-484.

Hogg, A.R. 1939. "The conduction of electricity in the lowest levels of the atmosphere." Mem. Commonw. Solar Obs., Aust. 7.

Kähler, K. 1927. "Die elektrische Raumladung der Atmosphäre in Potsdam." Met. Z. 44. pp. 1-5.

Kasemir, H.W. 1956. "Zur Strömungstheorie des luftelektrischen Feldes. III. Der Austauschgenerator." Arch. Met., Wien. A. 9. pp. 357-370.